FACULTY OF TECHNOLOGY

The effects of short-term regulation on habitat conditions of brown trout, Salmo trutta in the lowermost part of River Kalajoki and possibilities for mitigation

Louis Addo

Water Resources, Energy and Environmental Engineering

Master's Thesis

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Supervisors: Dr Hannu Marttila, Dr Kimmo Aronsuu

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ABSTRACT
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Abstract (200-300 words)

Tiivistelmä:

Pohjois-Pohjanmaan eteläosassa sijaitsevan Kalajoen alimman 45 km matkalla virtaama vaihtelee Hamarin voimalaitoksella harjoitettavan lyhytaikaissäännöstelyn vuoksi. Tämä vaikeuttaa hyvän ekologisen tilan saavuuttamista Kalajoen alaosalla. Tämän tutkimuksen tarkoituksena oli selvittää mallintamisen avulla nykykäytännön mukaisen lyhytaikaissäännöstelyn ja mahdollisen uoman kunnostuksen vaikutuksia kalojen elinympäristön määrään ja laatuun. Tutkimuksen osatavoitteet olivat 1) arvioida nykyisen lyhytaikaissäännöstelykäytännön intensiteettiä Kalajoen alaosalla, 2) tutkia 1D HEC-RAS-mallilla, kuinka eri virtaamatilanteissa harjoitettu lyhytaikaissäännöstely vaikuttaa virtaaman ja vedenpinnan vaihteluihin eri etäisyyksillä voimalaitoksesta, 3) tutkia nykyisen lyhytaikaissäännöstelykäytännön vaikutuksia kahden kosken (Juurikoski välittömästi voimalaitoksen alapuolella ja Hihnalankoski noin 32 km voimalaitoksen alapuolella) virtaama- ja syvyysvaihteluun sekä 4) tutkia 2D-habitaattimallilla lyhytaikaissäänöstelyn ja mahdollisten kunnostustoimenpiteiden vaikutuksia taimenen elinympäristön määrään ja laatuun. Hamarin voimalaitoksen nykyinen lyhytaikaissäännöstely luokiteltiin luokkaan suuri vaikutus (high impact), minkä perusteella sitä olis syytä lieventää. Tutkimuksessa havaittiin, että erityisesti korkealla virtaamalla lyhytaikaisäännöstelyn vaikutus ulottui aina Kalajokisuulle asti. Kun keskimääräinen tulovirtaama oli pieni tai keskimääräinen, lyhytaikaisäännöstelyn merkittävän vaikutuksen alue oli selvästi lyhyempi. Lyhytaikaisäännöstelyn vaikutus taimenen elinympäristön määrään ja laatuun oli huomattavasti suurempi Juurikoskessa kuin Hihnalankoskessa. Tähän vaikutti ennen kaikkea etäisyys voimalaitokseen, mutta myös Juurikosken morfologinen rakenne. Tulosten perusteella taimenen elinympäristön määrä ja laatu Juurikoskessa paranisi, jos sen rakenne muutettaisiin samalaiseksi kuin Hihnalankoskessa. Kuitenkaan pelkällä rakenteen muuttamisella ei voitaisi poistaa lyhyaikaissäännöstelyn haittavaikutuksia kuten kalojen kuivilleen jäämistä, sopivan elinympäristön siirtymistä lyhytaikaisäännöstelyn rytmissä sekä poikasten ja mätimunien huuhtoutumista. Tästä syystä kunnostustoimien lisäksi olisi lyhytaikaissäännöstelyä lievennettävä. Mahdollisia lievetämistoimia ovat mm. minivirtaaman nostaminen, maksimivirtaaman laskeminen ja juoksutusmuutoksien tekeminen mahdollisimman pienin portain.

Avainsanat: lyhytaikaissäännöstely, taimen, 1D ja 2D hydraulinen mallinnus, 2D-habitaattimallinnus, uoman kunnostus, säännöstelyn kehitäminen.

Additional Information

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Abstract (200-300 words)

The lowermost 45 kms of River Kalajoki in northern Finland experiences fluctuations in flow rate due to hydropeaking practise of Hamari hydropower plant (Hamari HPP). This has decreased good ecological status in the lower part of Kalajoki and affecting fish habitat condition. The main objective of this study is to investigate the effect of hydropeaking of hydropower power plants on fish habitat through field measurements and modeling, and suggest possible mitigation measures. The study specifically aims to (1) evaluate the level of current hydropeaking practice on lower part of Kalajoki, (2) investigate with 1D HEC-RAS model the extent to which hydropeaking practice affect the fluctuations in water surface elevation (WSE) downstream of the Hamari HPP, (3) investigate the impact of current hydropeaking regulatory practice on the morphological structure of two rapids on the Kalajoki namely; Juurikoski (located just below the Hamari HPP in Ylivieska) and Hihnalankoski (located about 32 km below Hamari HPP in Tynkä), and (4) investigate the with 2D fish habitat modeling. The effect of hydropeaking practice on the quality and quantity of fish habitat and possibilities for mitigation. In general, it was found that significant hydropeaking induced WSE fluctuations could impact all the way to the mouth of the Kalaojoki depending on the magnitude of discharges from the Hamari HPP. The state of hydropeaking below Hamari HPP was found to be 'high impact' and therefore needs improvement in the ecohydraulic state of the river. The current hydropeaking practise had a more negative effect on the quantity and quality of brown trout habitat at Juurikoski than Hihnalankoski partly due to the nearness of Juurikoski to the Hamari HPP and also partly due to its poor river construction compared to Hihnalankoski. This study explored the morphological restoration of Juurikoski with Hihnalankoski river structure and found a significant increase in fish habitat quantity in terms of weighted usable area (WUA) in excess of 200 % for all brown trout class. However, the morphological restoration alone cannot ensure total eradication of hydropeaking effects. Therefore an addition, appropriate operational measures regarding minimum flow adjustment, downramping rate, an adjustment in maximum allowable peak flows should be considered to help mitigate other unavoidable impacts such as stranding and flushing away of larvae, eggs and redds.

Keywords: hydropeaking, brown trout, 1&2D hydraulic modeling, 2D fish habitat modeling, River 2D, morphological and operational mitigation measures.

Additional Information

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SYMBOLS AND ABBREVIATIONS

CbSI	Combined Suitability Index
HPP	Hydropower plant
WUA	Weighted usable area
m^2 100^{-1} river reach or m^2/100mRR	Square meters per 100 m of river reach
rkm	River kilometres
cm/min	Centimetres per minute
m^3/s	Cubic meters per second
%	Per cent
°C	Degree Celcius
m, cm, km	Meters, centimeters , kilometers
1D	One dimensional
2D	Two dimensional
HEC-RAS	Hydrological Engineering Center's River Analysis System
XS	Cross-section
WSE or SWE	Water surface elevation
Q	Discharge

1 INTRODUCTION

1.1 Effect of hydropeaking on river ecosystem

Hydropeaking is a popular term that describes the rapid fluctuations in the discharge and water level of a river receiving water from the outlet of a peaking hydropower plant. A peaking hydropower plant is a type of hydropower plant that is operated or run in a few hours (hrs) to meet the peak electricity demand. Hydropeaking changes the natural flow regime of the river by changing the magnitude and timing of flow (Charmasson and Zinke, 2011) affecting the physical or abiotic conditions (*river depth, width, velocity*, *sediment load* and *water temperature*) of the river altering the natural habitat conditions of organisms living in the river (Person, 2013, p.16). For instance, the movement of riverbed material from rapid flow fluctuations from hydropeaking creates severe effects on the whole community structure in the river. Usually, the river stretches that have experienced hydropeaking exhibit reduced macroinvertebrate biomass and a change of community structure and species traits. (Graf et al., 2013). Fish larvae and juveniles are mostly affected by hydropeaking due to their preference for shallow water areas with low flow velocities which are continuously dewatered and watered by hydropeaking. (Schmutz and Sendzimir, 2018, p.98)

The natural flow regime is essential for the conservation and sustainability of the native biodiversity in the river ecosystem (Poff et al., 1997). A change in the river natural flow regime changes the abiotic or physical part of the river which defines the *morphology* (water depth, gradient, width, riverbed material and grain size), *discharge regime* (fluctuations in discharge, changes in mean, maximum and minimum flow, wetted area) and *water quality* (temperature, turbidity, oxygen concentration, nutrient concentration, pollution). These abiotic parameters of the river have a direct impact on the living conditions of the river ecosystem. The abiotic parameters impact river habitat diversity, spawning grounds, juvenile fish habitat, flushing, stranding, reproduction, and mortality. When these living conditions are affected, the species diversity and abundance of aquatic organisms (macrobenthos, fish) and Vegetation (phytobenthos, bank vegetation) are affected (Charmasson and Zinke, 2011). Castro et al. (2013) confirmed that hydropeaking has an influence on daily and seasonal invertebrate drift patterns whereas Bejarano et al. (2018) concluded that hydropeaking could impede on seed germination and plant performance of riverine plants. A field experiment conducted by Saltveit et al. (2001) on stranding in juvenile atlantic salmon (*salmo salar*) and brown trout (*salmo trutta*) showed that fast down-ramping from the abrupt reduction of discharge from hydropeaking could lead to stranding and mortalities to fish juveniles. In general, the natural flow of a river is very important because it is a key driver of aquatic biodiversity and defines the quantity and quality of instream physical habitat. Aquatic species are designed naturally to synchronize their development to the natural flow rhythm of the river and hence any changes to the natural flow could affect very important developmental stages of an aquatic organism (Maddock et al., 2013, p.230-231).

Another phenomenon associated with hydropeaking that acts as an additional stressor to river biota is thermopeaking (Bruno et al., 2013). During hydropeaking, the temperatures of the discharged water from the turbine and the receiving water in the river downstream have different temperatures depending on the season. The mixing together of the two waters causes cold or warm thermopeaking (Carolli et al., 2012). Thus the resulting water from thermopeaking becomes colder in the summertime and warmer in the wintertime due to the hypolimnic water releases for energy production (Zolezzi et al., 2011). Research has shown that thermopeaking has the potential of causing drifts in benthic species as benthic organic naturally relocated to find places in the water with better temperature (Maiolini et al., 2011; Zolezzi et al., 2011). In addition to thermopeaking, the fast and turbulent flow of water exiting the turbine causes the receiving river to be more turbid from the resuspension of solids. The turbidity affects the river quality related to oxygen content and water temperature (Person, 2013, p.17).

1.2 Effect of hydropeaking on fish habitat conditions

Despite the advantages of hydropower providing high reliability, flexibility and efficiency in the mixed electricity power system to support the energy needs (Gürbüz, 2006), it is important to note that peaking hydropower plants could have severe negative effects on the aquatic ecosystems including fish habitat which undermines the sustainability of river ecosystems (Person, 2013).

Fish habitat defines a place or a set of places which a fish or population of fish (including migratory fishes) can find physical and chemical features required for survival and existence. These features include suitable water quality, migration routes, feeding and resting sites, and shelter from predators and inimical weather (Orth and White, 1993) in (Hayes et al., 1996). It is evident that hydropeaking creates a problem for fish habitat below hydropower dam. Young et al. (2011) reviewed the advantages and disadvantages of hydropeaking against fish habitat changes. The disadvantages of hydropeaking can be (a) stranding: where fishes are separated from flowing water as the water level is reduced, (b) downstream displacement of fishes and (c) spawning habitat dewatering leading to reduced spawning and rearing success as a result of red dewatering and mistimed or obstructed migration. Some positive effects of hydropeaking can be (a) maintenance of rearing and spawning habitat through flushing away of fine sediments from gravel substrates which clogs up the spaces in gravel substrate and kills the fish eggs (b) biological cues to trigger spawning, hatching, and migration. Amongst all the adverse effects of hydropeaking, stranding is the most severe. Stranding could be categorized into *beach stranding* (where fishes are dewatered completely on their substrate) or *entrapped stranding* (fishes are left in small pools of water after down ramping (Young et al., 2011). Winter and summer beach stranding could have severe effects on atlantic salmon juveniles. Hydropeaking leads often also to obstruction to migration, loss of food and increased predation of juveniles especially during down-ramping (Young et al., 2011). The effect of hydropeaking on fish mortality is small (Vollset et al., 2016; Casas-Mulet et al., 2015b) however, the cumulative mortality over a long-term period especially for juveniles can be significant. Hydropeaking peaking at night is more harmful to fishes than day time hydropeaking due to poor visibility at night as water level ramps (Schmutz et al., 2015; Saltveit et al., 2001).

During fish migration to upstream areas, fish ladder allows the fishes to bypass the dam. High discharges from hydropower plant outlet lure migrating fishes to move towards hydropower plant tailwater outlet instead of the fish ladder decreasing the number of fishes going through the fish ladder and increasing fish density around the tailwater outlet of the hydropower plant. During hydropeaking or immediate abrupt shut down of hydropower plant, fish around the outlet of hydropower plant are stranded and killed as water ramps down very fast. On River Suldalslågen in south-west Norway, unexpected shutdown of hydropower plant led to fish mortalities near the tailwater outlet area after luring bypassing fishes to the tailwater water area instead of the fish ladder installed (Maddock et al., 2013, p.327). Other studies have shown that sudden discharge reduction in the river due to hydropeaking could cause high mortalities in fish juveniles (Saltveit et al., 2001) making them the most vulnerable fish size to the negative impacts of hydropeaking (Scruton et al., 2005; Scruton et al., 2008; Scruton et al., 2003) . This effect is severe in wintertime than summertime simply because they are less active and unwilling to move much (Person, 2013, p.37).

Hydropeaking can have an effect on the spawning behaviour of fishes but vary between different fish species. Under similar hydropeaking conditions, atlantic salmon are more likely to return to spawn even in shallow areas that have experienced repeated and abrupt discharge fluctuations provided the level of restoration is favourable for spawning. Brown trout, on the other hand, would like to use the low flow condition to spawn in areas not habitable by atlantic salmon. This spawning behaviour makes brown trout more vulnerable in terms of spawning in the shallow parts of the river. (Vollset et al., 2016) . Research work done by Schmutz et al. (2015) on the response of fish community concluded that the ramping rate and peak frequency both have an effect on the habitat condition of fish (Schmutz et al., 2015).

1.3 Mitigation measures against hydropeaking on fish habitat

The mitigation of hydropeaking on river ecosystem can be achieved by implementing changes in the operational and morphological measures of water use system of the river.

Operational Measures

An operational measure has to do with adjustment in hydropower plant outflow in a manner that does not disturb river organisms. This could be achieved by slowing down the upward and downward ramping rate through a slow start and stop of turbines, limiting and or increasing the minimum flow during critical periods, constriction of maximum peak flow and limiting of the drawdown range (Juárez et al., 2019). Such operational strategies would prevent fish stranding, drifting of macro-invertebrates, reduction of fish habitat, diversity and availability for spawning, fish eggs and juveniles. (Charmasson and Zinke, 2011, p12) (Person, 2013, p.23). The ramping rate, base- and peak-flow magnitude, peak frequency and time between peaks are altered by hydropeaking and would negatively impact fish species at different developmental stages.

Moreira et al. (2018) reviewed and collated from the scientific community and national regulations operational measures for mitigating the effect of hydropeaking at various stages of development. A description of some operational mitigation measures and hydropeaking thresholds for brown trout are as follows: (a) daytime downramping threshold of ≤0.1 cm/min and ≤0.05 cm/min during the night will reduce stranding of brown trout larvae, where thresholds of ≤6.4 cm/min (daytime) and ≤3.2 cm/min (night time) are recommended to reduce stranding of brown trout juvenile (65-75mm) (Auer et al., 2014). (b) Minimum flows from 10 m^3/s to 30 m^3/s from mid-November to mid-May will prevent dewatering of spawning grounds and ensure submergence of 90 % spawning grounds (Lascaux and Cazeneuve, 2008). (c) Ramping rates less than 0.25 cm/min increases the probability of achieving a higher ecological status in nature-like river channels (Schmutz et al., 2015). Yin et al. (2012) defined a way to appropriately set an operational measure to a hydropower plant, however, its single implementation as a measure to mitigate adverse effects of hydropeaking could create severe challenges to the hydropower business. Rather, combining operational and structural measures, for example, could be an economic win-win situation for hydropower business and environmental protection (Kopecki and Schneider, 2016). The following sub-chapters describes into to details issues of ramping rate, base- and peak-flow magnitude, peak frequency and time between peaks as applied to hydropeaking.

Rate of ramping

The ramping rate of a river, a term that describes how fast the water level of the river increases or decreases in response to peaking flow events has an influence on stream organisms. Downramping may lead to fish stranding whiles upward ramping may lead to drifting or river organisms. (Schmutz and Sendzimir, 2018, p.97). Several field and laboratory studies on the downramping induced stranding (Auer et al., 2014; Auer et al., 2017; Schmutz et al., 2013) in (Moreira et al., 2018) and (Young et al., 2011; Nagrodski et al., 2012) points to the fact that fish juvenile and larvae are the most affected fish life stage. Upward ramping introduces more water in the system at a short time which creates drifting problems for juveniles and eggs (Auer et al., 2017).

Saltveit et al. (2001) confirmed that an abrupt shut down of hydropower plant could increase mortality of juvenile salmonids. Rather, a gradual shut down of the hydropower plant would increase the down ramping time which would give vulnerable fishes (juveniles and alevins) some time to sense and reposition before they end up stranded. Applying a slower upward ramping would help reduce the impact of drifting of juvenile fishes (Auer et al., 2017). Ramping rates in general, impacts, the ecological status of the river (Schmutz et al., 2015). Since fishes are less mobile and often hiding in the substrate during the daytime, it is better for flow reduction to done after dark especially during winter (at water temperatures below 8°C) to reduce the risk of stranding (Maddock et al., 2013, p.329).

Base-and peak-flow magnitude, peak frequency and time between peaks

The magnitude of base and peak flow due to hydropeaking mostly affect negatively fish spawning and intra-gravel life stages. The peaking leads to dewatering of spawning grounds which in turn leads to the mortality of eggs and larvae. The dewatering of redds can kill pre-emergence of alevins due to their sensitivity to dewatered redds. To mitigate this effect, it is recommended to move the spawning time out of the regular peak-flows. Fish will spawn in the higher elevation areas during the regular high flow period which could easily run dry during base flow. A way to achieve this is by setting limits on the maximum flow during spawning to avoid flushing away of spawning habitat as well as providing the spawning areas with sufficient base-flow to prevent drying of spawning redds. (Moreira et al., 2018)

Morphological measures

The morphological heterogeneity of a river is essential for producing different habitat for biotic communities (Bruder et al., 2016). It has been demonstrated that hydropeaking impacts in a river are strongly dependent on river morphology (Vanzo et al., 2016b).

Person et al. (2014) reported that under hydropeaking conditions, the monotonous river reaches demonstrated low habitat suitability than braided reaches. The channelized river reaches usually have low morphological heterogeneity and hence poor habitat diversity (Ribi et al., 2014). Some morphological elements such as low-gradient banks or gravel bars can increase the risk of standing due to faster dewatering of wetted area during hydropeaking. (Bruder et al., 2016). Morphological measures have to do with engineering the river to for example increase the flood evacuation capacity, dampening of peak flows and providing refuge habitats for fish. (Person, 2013, p.35). Morphological restoration of hydropeaking affected reaches would help improve diverse habitat for biotic community.

1.4 Fish habitat models

Since the natural flow regime of a river has a direct effect on the physical habitat of its resident fishes, it is imperative as part of water management procedures to access the extent to which these alterations in the natural flow regime impacts the fish habitat. Away to do this is through instream fish habitat modeling (Pearson, 2013, p.24). In general, fish habitat models present themselves as tools for simulating the impact of modifications in river discharge on the instream fish habitat for different developmental life stages of aquatic organisms. Fish habitat modeling is an important tool for studying the ecological functions of a river by presenting an opportunity to quantitatively and qualitatively assess habitat conditions for indicator species. (Schneider et al., 2010, p.5). Fish habitat models can be used to evaluate the habitat suitability of a target species based on the species preferred suitable physical variables in terms of *water depth, flow velocity* and *substrate conditions* of the river (Mouton et al., 2007). Fish habitat model uses the biophysical relationship as a basis to predict the suitability of fish habitat and how environmental factors such as hydropeaking affect the distribution and communities of fish species in the river (Conallin et al., 2010)

Fish habitat models present an opportunity to study the effects and restoration measures of rivers affect by hydropeaking. In recent times, fish habitat models have been used as an important management tool to evaluate the effect of hydropeaking on the habitat of aquatic biota including fishes (Kopecki and Schneider, 2016; Juárez et al., 2019). The next chapter explains the general principle behind fish or aquatic habitat models.

General Principles of Fish Habitat Models

Fish habitat models are part of physical habitat simulations models and therefore follows the procedure outlined by Bovee (1982). The working principles of a fish habitat model are based on the following three facts that connect the relationships between river biotic conditions and the preferred abiotic conditions of a target fish species (Bovee, 1982). As found by Bovee (1982), (1) each target species of fish has a range of preferred habitat conditions that it can tolerate. (2) These ranges of preferred habitat conditions for a target fish species can be described quantitatively. (3) Finally, the area in the stream providing these conditions can be quantitatively described as functions of discharge and channel structure making it possible to quantitatively access habitat conditions for different river discharges. (Yrjänä, 2004, p.19).

Fish habitat models comprise of three sub-components which work together to give out habitat conditions for a target fish species for specific river discharge. These sub-components are (1) a hydrodynamic model which models temporal and spatial variation of river abiotic conditions such as depth, velocity and substrate conditions, (2) biological habitat preference data of the target species which will form the basis of the suitability of the target species for a given discharge and (3) and habitat model which combines the results of hydrodynamic model and habitat preference data to define the habitat suitability of the target species under study. (Person, 2013, p.30)

There are generally two indicators that are used to evaluate the habitat suitability of a river. These are ***weighted usable area (WUA)*** (Bovee, 1982) and **hydraulic habitat suitability index (HHS)**. These two indicators are computed based on habitat suitability index (HSI) for a given flow or river discharge (Q). (Tuhtan et al., 2012). A detailed description of the HSI, HHS and WUA and their mathematical equations are presented below.

Habitat suitability index (HSI): This parameter is measured on a scale for 0 (not suitable) to 1(most suitable) and can be presented on a habitat suitability maps for the investigated discharges. Based on the preference values for each abiotic parameter (velocity, depth, and substrate), HSI could be calculated using the product equation, the arithmetic mean or the geometric mean. For example, the equation for the geometric means is shown in equation 1. The suitability index for each cell could in some cases be measured as a simple product of the suitability values for depth, velocity and substrate as shown in equation 2 (Person, 2013, p.34).

$$SI_i(Q) = \sqrt[3]{P(H_i(Q)) * P(U_i(Q)) * P(S_i(Q))} \tag{1}$$

where

$SI_i(Q)$ *is the suitability index in the i-cell for the discharge Q*

$P(H_i(Q))$ *is the suitability value for flow depth* H_i *for the discharge Q*

$P(U_i(Q))$ *is the suitability value for velocity* U_i *for the discharge Q*

$P(S_i(Q))$ *is the suitability value for the substrate* S_i *for the discharge Q*

$$SI_i(Q) = P(H_i(Q)) * P(U_i(Q)) * P(S_i(Q)) \tag{2}$$

where

$SI_i(Q)$ *is the suitability index in the i-cell for the discharge Q*

$P(H_i(Q))$ *is the suitability value for flow depth* H_i *for the discharge Q*

$P(U_i(Q))$ *is the suitability value for velocity* U_i *for the discharge Q*

$P(S_i(Q))$ *is the suitability value for the substrate* S_i *for the discharge Q*

Weighted usable area (WUA): This represents the total area available habitat for a given discharge. WUA gives an absolute value for the overall habitat quality of a reach. WUA is computed as the sum of each wetted cell for a given discharge. This can be seen in equation 3 below.

$$WUA(Q) = \sum_{i=1}^{n} A_i * SI_i(Q) \tag{3}$$

where

$WUA(Q)$ *is the weighted usable areqa for a given discharge Q* $\left[m^2\right]$

A_i *is the area of the i-cell* $\left[m^2\right]$

$SI_i(Q)$ *is the suitability index of i-cell for a given discharge Q*

Note that usually WUA is measured in ($m^2 100 m^{-1}$river reach)

Hydraulic habitat suitability index (HHS): This parameter is calculated as the ratio of WUA to the total wetted area for a given discharge. The suitability of the physical habitat variables for a target species is given by HHS. Mathematically, HHS is calculated by equation 4;

$$HHS(Q) = \frac{WUA(Q)}{WA_{tot}} \tag{4}$$

where

HHS(Q) is the hydraulic habitat suitability index for a given discharge Q

WUA(Q) is the weighted usable area for a given discharge Q $\left[m^2\right]$ *and*

WA_{tot} *is the total wetted area* $\left[m^2\right]$

1.5 Hydraulic and hydrodynamic models

The hydrodynamic part of the fish habitat model computes water depth, velocity for determining habitat suitability at different discharges. The hydraulic models make it possible to determine flow properties (velocity and depth) at different sections of the river course for different discharges. There are several methods of predicting flow properties. Since the type of hydraulic modeling method has an influence on the overall results of the fish habitat model, gaining an insight into the various types of hydraulic models, their limitations, and their pros and cons would help improve on the reliability of the model results beforehand. The next chapter describes the different types of hydraulic modeling, their limitations and the most recommended option for fish habitat modeling nowadays for in-stream fish habitat modeling.

Types and most preferred Hydrodynamic modeling tools used in in-stream habitat modeling

Computational fluid dynamics is the basis of modeling the hydrodynamics of the river in a natural stream. There are several methods used to predict river properties. These methods could be *one dimensional (1D), 2D, 3D or non-numerical hydraulic modeling*. 1D, 2D and 3D hydraulic models solve momentum and conservation of mass equations and are based on spatial information of hydraulic modeling in one, two and three dimensions respectively. The 1D hydraulic model represents flow properties in one direction (longitudinal or downstream direction along x). 3D represent flow properties along 3 directions (longitudinal or downstream direction along x, a transversal direction along y, and vertical direction along z). 2D represents flow properties along 2 directions (either longitudinal or transversal directions or longitudinal and vertical directions). The non-numerical hydraulic modeling involves field measurements, analytical solution and statistical analysis of flow field. (Maddock et al., 2013, p.31-32)

Although 3D models have an advantage of providing important information on spatial flow properties variation especially at small scales, normal 2D modeling is a much preferred hydraulic model choice in ecohydraulics compared because of cheaper the computational cost (Niayifar et al., 2018). Thus 2D model is cheaper and faster to use compared with 3D. The 1D and non-numerical hydraulic model has a limitation that makes them less preferred nowadays. The major limitations of the 1D hydraulic model are shown in a later chapter below. The non-numerical hydraulic models have limited utility in complex rivers especially braided, pool-riffle and meandering rivers because their basis on cross-sectional measurements, issues related to how the flow measurements are taken and the limitations of their statistical models. (Maddock et al., 2013, p.32). Adeva-Bustos et al. (2019) studied the effect or specific morphological changes to the Ljungan River in Sweden which had been heavily modified by timber transportation and hydropower regulation. The study used 2D modeling (HEC-RAS 5.0) to restore the Ljungan River to support fish habitat. The results showed that indeed hydraulic models have the potential to simulate hydraulic conditions of the river before and after river modification and the effect of fish habitat because the implemented restoration modification showed an improvement in fish spawning and nursery areas comparing the pre- and post-modification hydraulic condition of the river.

The biological fish preference of the target fish is presented as ***preference curve*** or ***fuzzy logic rules***. The following explains into details the description of fish habitat suitability in fish habitat modeling.

1.6 Fish habitat suitability preference

The flow regime of a river strongly affects the abiotic conditions of the river. According to Person (2013), substrate conditions, flow velocity and depth are the three most relevant abiotic parameters that could very much affect fish habitat. A classical approach of measuring habitat suitability is by comparing the similarity between the existing and preferred conditions of target species and describing it on a scale. The habitat suitability index (HSI) is one such common index that describes the biological response of a river organism to the abiotic attributes. Typically HIS is measured on a scale from 0.0 (unsuitable) to 1.0 (most suitable). This connection between the biological response and abiotic condition could be resolved in two ways. ***Univariate methods*** (when considering individual habitat variables) and ***multivariate approaches*** (taking into account interactions between habitat variables to determine the target species or life stage response to abiotic factors). Another index that can be used to measure the habitat suitability of a target species or life stage as a function of river flow rate is ***weighted usable area*** (WUA) or ***hydraulic habitat index*** (HHI) which is based on the integration of the HSI and hydraulic characteristics. Note the HHI which is computed by dividing WUA by the wetted perimeter to get an index ranging from 0.0 to 1.0. The reason for this is to eliminate the influence wetted area to make it possible to compare between study sites. (Maddock et al., 2013, p.76). Fish habitat preference as used in instream physical models in biologically expressed in terms of Habitat Suitability Curves (HSC) and fuzzy rules (Person, 2013, p.24).

Habitat Suitability Curves (HSC) and Habitat Rating Curves (HRC)

HSCs are curves that describe the relationship between abiotic conditions of the river and the suitability of a specific target species of fish on a scale of 0 to 1 where 0 means not suitable and 1 means most suitable. Typically habitat suitability for a specific target species of fish is made for water depth, velocity and substrate particle size (see figure 5-7). Note that these suitability curves are typically made by biologists for specific rivers for a specific target fish species but in some cases results from several rivers are combined to form a regional suitability curve that can be used for rivers within that region. HRCs show how the area of suitable habitat for species and communities of river organism varies with varying river discharges making it easy to evaluate habitat quantity at any given river discharge within the range of surveyed discharges in the curves (Maddock et al., 2013, p.110). This makes it possible to evaluate how hydropeaking affects fish habitat by evaluating how changes in the river discharge affect suitable habitat availability for a particular species and life stage of fish.

Fuzzy rules

Fuzzy rules present an alternative to the classical approach of using fixed numerical values and exact functions to describe habitat suitability. It uses “high”, “medium”, and “low” to describe physical properties (water depth and flow velocity) of the river. The use of fixed numerical values and exact functions are unable to capture the complexity of natural systems (Schneider et al., 2010, p.7). The transitions in natural ecology are not crisp but gradual. The fuzzy approach an excellent model technique to deal with ecological gradients as the overlapping fuzzy set theory reflects these gradual transitions between predefined classes. A major advantage of as mentioned by Person (2013) of fuzzy logic is that it allows for the use of qualitative data for numerical processing and provide the ability to consider multivariate effects without assuming independence on input variables. (Maddock et al., 2013, p.76). Thus the fuzzy logic combines hydraulic habitat and morphologic requirements in a non-schematic way that can significantly overestimate the amount and quality of habitat and which may in some cases omit certain key parameters necessary for the description of the habitat of certain species (Schneider et al., 2017). The user-specific parameters can be easily included together with the ability to take into account the interactions of the parameters without the explicit assumptions regarding parameter independence. (Schneider et al., 2010). Fuzzy rules used IF-THEN rules similar to the usual thinking pattern of the human brain (Person, 2013).

1.7 Life stage development of river brown trout

River brown trout (*Salmo trutta*) is an example of anadromous fishes (dwells in both fresh and salty seawater) with similar life stages as atlantic salmon (*salmo salar*). Adult female brown trout migrate from the sea into upstream of the river to dig nests into gravel substrate where they lay their eggs. The eggs are hatched into alevins where the depend on yolk sac as a primary source of nutrition. The alevins develop into juveniles and continue to stay in the rivers before they mature into smolts (enough to migrate to the sea). Smolts in the sea mature into adults then return to their native rivers for spawning during the summer to spawn to continue their life cycle. (Rulé et al., 2005)

Habitat use and selection

The selection of suitable habitat by salmonids is ecologically important and very much dependent on the ecohydraulics of the river, age and on the season or time of the year. During the winter, brown trout are duller in their foraging habits and spend the day hiding undercover whiles during the summer brown trouts are more active at dawn and dusk. In general, brown trout would select microhabitat to maximize net energy intake to avoid predation and competition (Jenkins and Keeley, 2010). Physical and biological factors have been identified to influence the macro, micro and meso-habitat use and selection of brown trout. Apart from temperature, and light, frequency and amplitude of water flow are physical landscape factors that affect the availability and distribution of different habitats. Competition within the same and different species of salmonids has an effect on the habitat use of brown trout. For example, fish size defines the dominance of habitat use. Thus large size brown trout dominates the smaller size brown trout. In the river inhabited by both brown trout and atlantic salmon, brown trout tends to be more aggressive and domineering suppressing the feeding of atlantic salmon displacing them to the fast-flowing areas of the river. In the situation where there are low densities of competition and predation, habitat suitability and fish abundance are controlled by abiotic habitat factors. However, when there are high densities of competition and predation, the biological factors control the habitat suitability and fish abundance irrespective of whether abiotic conditions are favourable or not. (Maddock et al., 2013, p.159-170).

The physical or abiotic conditions that affect habitat use and selection of brown trout are water depth, water velocity, substrate particle size and cover. For example river velocity meso- and microhabitat use in brown trout. Water flow fluctuation created by hydropeaking apart from stranding reduces the slow-flowing stream margin habitat in the river mostly preferred by juvenile trout and trout at the swim upstage. As the trout increases in size, the habitat preference moves into the deeper and faster flowing middle parts of the river. Thus large brown trout prefer the pools. (Maddock et al., 2013, p.159-170)

1.8 In-stream Aquatic Habitat Simulation Models and their limitations

Dating back into the 1970s, an aquatic habitat simulation tools for fish has been used in water resources management to evaluate the effect of flow regime alteration on the aquatic ecosystem as a basis to quantify and predict ecological impacts. The Physical Habitat Simulation (PHABSIM) model (Bovee, 1982) which is based on the concept of In-stream Flow Incremental Methodology (IFIM) is believed to be one the first simulators to have been used on habitat aquatic biota. PHABSIM are generally made up of three components. The first component is a hydraulic model that models the spatial and temporal variation in river depth, velocity and substrate conditions. The second component has a biological data which contains the habitat use and preference data of a target fish species. The third component is the habitat model which combines the hydraulic model with the biological data to determine habitat availability for a target species of fish under different river flow condition (Person, 2013, p.24).

PHABSIM was used to forecast Chinook salmon's preferred spawning habitat (Shirvell, 1989). Armitage and Ladle (1989) used PHABSIM to study habitat preference of target species. There were other habitat simulation models that were built based on the concept of PHABSIM. All the PHABSIM based models connect physical variables to habitat suitability by mean of uni- or multivariate preference function (Mouton et al., 2007) and were used to quantify the microhabitat area per unit length of stream (Person, 2013). ***The Norwegian River System Simulator (SS)*** was one such model based on the PHABSIM. RSS has three parts namely; the database, the simulation models and the user interface. The data was based on a common logical data model which ensured data for the physical system was always stored in one database. The model had 14 different types of models integrated within on system. (Killingtveit and Fossdal, 1970; Alfredsen and Killingtveit, 1996). ***The River Hydraulic Habitat Simulation model (RHYHABSIM)*** (Jowett, 1989) was another habitat simulation model based on

PHABSIM. RHYHABSIM was able to model habitat responses of changing hydrological conditions and hence was considered a management tool for assessing ecosystem conditions. RHYHABSIM was used to model the response of habitat area for spawning and juvenile brown trout to varying streamflow (Thorn and Conallin, 2006). The authors pointed it out that RHYHABSIM did not include all factors that affect ecosystem function and hence the carrying capacities of streams for indicator species such as fish. ***EVHA*** was another habitat simulation model based on the PHABSIM. It used the graphical approach and included a model for validation of topographic data and for the calibration of the hydraulic model. The user of the model needs to consider the habitat or physical variables based discharge, maps, cross sections, and longitudinal profiles. EVHA uses three variables: WUA, a 100m normalized WUA and the habitat value. (Ginot, 1995). The ***Mesohabitat Simulation Model (Meso-HABSIM)*** was another PHABSIM based model developed by Parasiewicz (2001) with the main purpose of overcoming some of the challenges with PHABSIM with regards to its application on larger scales. All these habitat models operate by the same general principle described in **Chapter 1.7** except the type of hydrodynamic model used.

The major challenges with these PHABSIM based habitat simulation software are: (1) PHABSIM only used one-dimensional (1D) routine in its hydraulic model to compute water surface elevation for velocities for each cross-section. 1D habitat models neglect the transverse flows and eddies which are an important component of naturally flowing river simply because 1D assumes river flows in parallel line(Wu et al., 2006). Thus, a naturally flowing river or stream has varying depth, velocity, and multiple diverging flow paths which create uncertainties in the model results of 1D fish habitat models based on PHABSIM. Since the complex flow patterns of river are ecologically relevant to structural designs, any wrong predictions due to uncertainties of a 1D habitat model would create problems for the resulting structural design solution (Shields Jr et al., 2004). Casas-Mulet et al. (2015a) concluded the use of 1D hydrodynamic modeling as a tool for the estimation of potential stranding areas in rivers concluded that the 1D does not have the detailed cross-section required for better results for that kind of studies rather, the use of a 2D hydrodynamic model would be better. Vanzo et al. (2016a) found out that the use of a 2D hydrodynamic modeling gives a more accurate description of wetted perimeter variation and dewatering ramping rate. Other studies have shown that the use of a 2D routine would better capture the spatial changes in depth and water velocity with structural modifications in the river reach (Crowder and Diplas, 2000). Boavida et al. (2011) used 2D hydraulic model to measure the effect of WUA from the differences in-stream structures (lateral bays, deflector and islands) to improve habitat conditions of two critically endangered fish species Odeloucha River in Southwest Portugal. Person (2013) mentioned that PHABSIM based models do not integrate dynamic flow fluctuation. Additionally, PHABSIMs use an independent habitat suitability curve but in reality, habitat suitability curves are not independent (Mouton et al., 2007) .

General working principle of current 2D hydraulic models in Fish habitat modeling

Current knowledge on fish habitat modeling utilizes 2D hydrodynamic modeling for non-homogeneous river stretches as the hydraulic model option due to their advantages over 1D, 3D and non-dimensional hydraulic modeling. Example of 2D hydraulic models currently used include HEC-RAS 2D (Adeva-Bustos et al., 2019), SRH-2D (Tuhtan et al., 2012), River 2D (Almeida et al., 2016), and Hydro AS-2D (Person, 2013). The procedures for computing 2D hydraulic computation modeling are very similar. The bed elevation or bathymetry of the river reach under steady is derived through bed elevation measurements with Global Positioning System (GPS) and or with Acoustic Doppler Current Profiler (ADCP) for better bathymetry. Mesh square or tin cells are made to represent the surface.

The meshing is done with either external or inbuilt software depending on the type of 2D hydraulic model used. For example, Hydro AS-2D and SRH- 2D uses Surface Water Modeling System SMS for mesh generation (Lai, 2008) whiles River 2D has an inbuilt meshing model that comes with a software package (Steffler and Blackburn, 2002). Hydrologic Engineering System River Analysis System (HEC RAS-2D) uses both SMS and AutoCAD Civil 2D for mesh generation.

Discharge measurement measurements are collected to define boundary conditions and to run either unsteady or steady flow. For example, HEC-RAS 2D, SRH-2D. Hydro AS 2D can perform both unsteady and steady flow analysis. River 2D computes transient flow computations that converge into steady-state conditions (Steffler and Blackburn, 2002, p.20). All 2D-hydrodynamic models required calibration with observed measured water surface level to ensure model reliability. Usually, the calibrated parameter is the Manning 'n' value for different sections of the river reach. After calibration and different discharges can be modeled and passed to the Fish habitat model to perform suitability maps for different discharges.

General working principle of current Fish habitat models

Current research has shown different physical habitat simulation models for the river restoration.Tuhtan et al. (2012) and have used Computer-Aided Simulation for Instream Flow Reparia (CASiMiR) (Jorde et al., 2000; Schneider et al., 2001) to evaluate the effect of hydropeaking on the fish habitat of Juvenile European grayline and brown trout respectively in Europe. A detailed description of CASiMiR can be seen in a later chapter.

1.9 Habitat model software (HMS)

The Habitat Model Software (HMS) is a physical habitat model developed by North Arrow Research Ltd. This model has a concept that is same as the CASiMiR software. It is built to receive natural river bathymetry in geo.tiff file for hydraulic simulation. It takes in aquatic organism habitat preference as input in the form of Habitat Suitability curves and fuzzy logic rules. Its computes habitat suitability of a target species based on WUA and normalized WUA (Bouwes et al., 2011). Since there is not much information about the real use of this model it was not considered as a fish habitat model of choice for this study.

1.10 River 2D fish habitat model

River 2D is a combined 2D hydraulic and fish habitat model that can be used for instream habitat simulation. Boavida et al. (2013), Almeida et al. (2016) and Koljonen et al. (2013) have used for fish habitat simulation for various studies. Koljonen et al. (2013) used River 2D Fish habitat model to study the in-stream restoration of juvenile Atlantic salmon in River Kiiminkijoki in northern Finland. The result of this study proved that indeed the combination of 2D hydraulic modeling and biological monitoring is a promising approach to stream restoration assessment. Both Boavida et al. (2013) and Almeida et al. (2016) have used River 2D fish habitat model to study the effect of hydropeaking on different rivers. Both Boavida et al. (2013) concluded that River 2D is a powerful tool for assessing the influence of rapid flow changes in fish habitat typically caused by hydropeaking. A detail description of River 2D and its working procedure is shown below.

Background of River 2D

River 2D as the name suggests is a two-dimensional (2D) depth-averaged hydrodynamic and fish habitat model for studies that require local details of velocity and depth distributions in natural streams and rivers. The model was developed at the University of Alberta (Ghanem et al., 1994a; Ghanem et al., 1994b). Bridge design, river training and diversion works and contaminant transport are other engineering tasks which can utilize the functions of the River 2D model due to its ability to perform 2D hydraulic modeling. Just like other 2D models, River 2D is a finite element model solves basic mass and momentum conservation equations.

The data requirements of the 2D hydraulic part of River 2D model are; channel bed topography, roughness and transverse eddy viscosity distributions, boundary conditions and initial flow conditions. River 2D has an in-built mesh model that creates discrete mesh or grids within which flow variations are captured. An accurate bed topography data is very crucial for the reliability of the model results. It is advisable to combine GPS and depth sounding measurement to acquire good bed topography data. Bed roughness is directly from manning n values. The model is calibrated on measured water stages before using the model for any use.

Principles of 2D hydrodynamic modeling of River 2D

The physics behind the working principle of River 2D is based on the conservation of mass and momentum.

The conservation of mass principle states that if a rectangular box of depth H and plan dimensions Δx and Δy are considered, the rate of change of the water volume in the box is equal to the resultant rate of water flow into the box. This is expressed and simplified in the differential mathematical equation of mass continuity shown below in equation 5.

$$\frac{\partial H}{\partial t}+\frac{\partial(q_x)}{\partial x}+\frac{\partial(q_y)}{\partial y}=0 \qquad (5)$$

where H is depth of water in the rectangular box

$\frac{\partial(q_x)}{\partial x}$ *is the dicharge per unit width component in the logitudinal or x axis*

$\frac{\partial(q_y)}{\partial x}$ *is the dicharge per unit width component in the lateral or y axis*

$\frac{\partial H}{\partial t}$ *is the dicharge per unit time component in the depth axis*

The continuity equation presents one relationship for depth and two velocity components at every point in the flow. In order to solve one equation and two unknown variables, another equation is required to solve the equation. This other equation is derived from the conservation of momentum equation. The conservation of momentum for the same assumed rectangular box states that the rate of change of x momentum with time in the box is equal to the net rate on the inflow of x momentum across the sides of the box plus the net force acting on the box in the x-direction. This is summarized in a differential equation given by equation 6 below

$$\frac{\partial q_x}{\partial t}+\frac{\partial}{\partial x}\left(Uq_x\right)+\frac{\partial}{\partial y}\left(Vq_x\right)+\frac{g}{2}\frac{\partial}{\partial x}H^2 \tag{6}$$

$$\Rightarrow gH\left(S_{0x}-S_{fx}\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial x}\left(H\tau_{xx}\right)\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}\left(H\tau_{xy}\right)\right)$$

Typically a 2D form of Mannings equation is used to calculate the friction slope

The friction slope $\left(S_{fx}\right)=\frac{n^2U\sqrt{U^2+V^2}}{H^{4/3}}$

The transverse shear τ_{xy} *is computed by Bousinessq type eddy viscosity given by;*

$$\tau_{xy}=\nu_t\left(\frac{\partial U}{\partial y}+\frac{\partial V}{\partial x}\right)$$

Note that n and ν_t *are not constants or fluid properties but depend onflow situation*

The conservation of momentum in the y-direction is given by equation 7

$$\frac{\partial q_y}{\partial t}+\frac{\partial}{\partial x}\left(Uq_y\right)+\frac{\partial}{\partial y}\left(Vq_y\right)+\frac{g}{2}\frac{\partial}{\partial y}H^2$$

$$\Rightarrow gH\left(S_{0y}-S_{fy}\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial x}\left(H\tau_{yx}\right)\right)+\frac{1}{\rho}\left(\frac{\partial}{\partial y}\left(H\tau_{yy}\right)\right) \tag{7}$$

H is the depth of flow , U and V are the depth averaged velocitiesin the x and y coordinate directions respectively whiles q_x *and* q_y *are the discharge intensities in the x and y directions.*

q_x *and* q_y *are related to the velocity components through equations 8 and 9*

$$q_x=HU \tag{8}$$

$$q_x=HV \tag{9}$$

g is acceleration due to gravity

ρ *is density of water*

S_{0x} *and* S_{0y} *are bed slopes in x and y directions respectively*

τ_{xx}, τ_{xy}, τ_{yx}, *and* τ_{yy} *are the components of the horizontl turbulent stress tenor.*

The derived equations for 2D hydrodynamic modeling in the River 2D has a major drawback when modeling river reaches with steep slopes and dune bedforms. River reaches with steep slopes (10 % or steeper) and rapid changes of bed slopes such as dunes are not modeled accurately by River 2D due to the hydrostatic pressure distribution in the vertical. Coriolis and wind forces are assumed to be negligible whiles the distribution of horizontal velocities over the depth is assumed constant.

Simulation procedure from Hydrodynamic simulation to Habitat Simulation

The River 2D model packages have four sub-models. These are a bed mesh generation model called R2D-Mesh, a bed elevation model for generating the topography, Ice cover model for modeling surface ice cover and main River 2D model which does the hydraulic and fish habitat modeling. A summary of the sequence of modeling process and procedure from data collection to fish habitat simulation is described below.

The river bed elevation for the river reach is arranged in an appropriate order and saved in notepad format. The notepad file containing the river bed elevation is exported into the ***River 2D Bed model*** where the exterior boundary of the study reach is defined. The results from the River 2D Bed model is exported into ***River 2D Mesh model*** where the mesh is generated for the 2D hydrodynamics computations. The results from the mesh model are then exported into the ***River 2D Hydrodynamic model*** where appropriate boundary conditions, manning n value, and flow conditions are set to perform the hydraulic computations. After the completion of 2D hydrodynamic modeling, the *channel index data* and *preference data* for the target fish species is loaded into the ***Fish habitat model*** to run Fish habitat suitability for the target fish species.

A new model the currently receiving much attention instream habitat modeling is the modern versions of the

1.11 CASiMiR

The Computer-Aided Simulation for Instream Flow Requirement (CASiMiR) was developed in the 1990s by the Institute of Hydraulic Engineering at Stuttgart in Germany. CASiMiR was developed in response to the objective of developing a more sophisticated and ecology-related minimum flow solutions for assessing hydropower plants diversion. In 1996, CASiMiR was developed for fish preference application. (Moreira et al., 2018). The essence of the software is to assess the ecological integrity of rivers providing quantitative information of habitat qualities for fish, benthic invertebrates and macrophytes. CASiMiR can be applied to solve problems related to flow regulations, structural quality, effects of river regulations, river restoration and watershed management. (Schneider et al., 2001). Just like the other instream physical model, CASiMiR requires physical and biological parameters to determine habitat suitability for a target species. The model is able to utilize both Habitat Suitability Curves (HSCs) and fuzzy rules. (Person, 2013) CASiMiR has a special model for fish habitat modeling called CASiMiR-Fish.

The CASiMiR – Fish software presents a unique advantage of the possibility to use fuzzy logic which gives a better quantity and quality of fish habitat. CASiMiR uses a straight forward calculation that is easily understood. CASiMiR-Fish could be used to model fish habitat suitability based on a 2D hydrodynamic modeling unlike the PHABSIM based physical habitat model Thus CASiMiR- Fish has a 2D hydraulic interface that is capable of processing 2D hydraulic data. (Schneider et al., 2010).

Input and output data

The model input data are river bathymetry and hydrological conditions for the river reach under study and the habitat suitability curves for the three main abiotic parameters; depth, velocity, cover and substratum for the target species under study. The out of the model is the habitat suitability as number between 0 ans 1 (Person, 2013)

How CASiMiR evaluates habitat quantity and quality.

In the CASMiRi-fish model, the integrated distribution of changes in habitat suitability in the river (steady discharge conditions) understudy on could be assessed based on three parameters namely; *Habitat suitability index (HSI), Weighted usable area (WUA)* and *Hydraulic habitat suitability index (HHSI)*. (Person, 2013, p.26-27) (Schneider et al., 2010, p.22).

Case Study Applications of CASiMiR

CASiMiR was used in ecosystem services as a tool to investigate the operational and structural measures to mitigate the impacts of hydropeaking on fish larvae (grayling) on River Leach located in south Germany due to their vulnerability of limited swimming ability and stranding from downramping and drifting from upramping. This study used as 2D hydrodynamic modeling (SRH-2D) and CASiMiR model (GIS version). The fuzzy logical was applied. The study showed that adjustments in operational strategy by slowing down **downramping discharge** from **100m^3/s/hour** to **50m^3/s/hour** increased the suitable grayling habitat by 50%. From a structural point of view, this study showed that river that has side-channel provided suitable habitat for spawning, larvae and juvenile fish. Despite the advantage downramping it could affect meeting demands. It is, therefore, better to combine both operational and structural options to find a good balance for sustaining the hydropower business and river ecosystem. (Kopecki and Schneider, 2016)

Similary, Tuhtan et al. (2012) used 2D hydrodynamic modeling (SRH- 2D), CASiMiR fish, and fuzzy logic to study stranding risk of European grayling (*Thynallus thymallus*) due to hydropeaking on River Inn located at the Swiss Austrian Border. The authors concluded that stranding risk was more driven by the initial flow rates and not the absolute change in the flow rate. The river reaches with high amounts of habitat suitability index (HSI) with steep side slope are most likely less vulnerable to rapid flow fluctuations than the flatter and more heterogeneous reaches. Finally, instream structural measures (design of instream fish shelters) to mitigate the impact of hydropeaking.

Person (2013) studied the effect of hydropeaking on juvenile brown trout on Vordehrein river located in Surselva, Switzerland. This study was done using Habitat suitability curves (HSCs) for the biological preference, a 2D hydrodynamic model (Hydro AS 2D) and CASiMiR (fish habitat model). The results showed a severe impact of hydropeaking on juvenile trout in the winter period than in the summer. Thus a high fluctuation ratio of 10 to 15 times in winter and 1.5 times in the winter leads to the reduction in physical fitness of juvenile trout (Person, 2013). Adult Brown trout are less affected by hydropeaking than juvenile and spawning adult that require shallow shore habitat. The author mentioned the use of HSCs could create uncertainties in they are regionalized. It's better to have HSCs for the particular river understudy than to use one which represents an entire region as there could be a significant difference for different rivers within the region. Another study in Person (2013) applying the same methodology on Vorderrhein River, Surselva District, Switzerland concluded that although habitat could be available under hydropeaking condition. These habitats are impaired by the fluctuating flow which causes significant shifts or dewatering. However braided rivers turn to have less impact of this nature due to the buffer zone created by virtue of the form of the river just as observed in the side channels in the work of (Kopecki and Schneider, 2016)

1.12 Limitations of CASiMiR fish 2D and justification for choosing River 2D as the ideal fish habitat model for this project

CASiMiR Fish 2D which is the current version of CASiMiR Fish habitat models which support 2D fish habitat modeling with 2D hydrodynamic modeling interface. Thus CASiMiR Fish 2D allows the user to choose specific 2D hydrodynamic models including SRH-2D, River 2D, Hydro As-2D, Basment and Feswms. With the exception of River-2D the other 2D hydrodynamic models either use third-party models for mesh generation such as SMS which are expensive. CASiMiR Fish 2D itself was not a free open source software rather it was for sale for commercial purposes except for academic use which required the user or student to be compulsorily trained by developer of the model before the model was released to the student for use. The cost of CASiMiR fish 2D and or training, SMS mesh generation software made River 2D the best option considering the cost and simplicity of model. Above all River 2D was a combined 2D fish habitat and hydrodynamic model.

1.13 Objective and scope of the study

The goal of this study is to qualitatively and quantitatively investigate the effect of current operational strategy of short-term regulated hydropower power plants on fish habitat conditions at the lower part of Kalajoki (Ca.45 [rkm], thus river reach between Hamari Powerplant to the mouth of the Kalajoki). The target fish species in this study is brown trout (***Salmo trutta***). This study requires a 2D hydraulic and fish habitat modelling of the river flow properties to be implemented in a 2D fish habitation model. Based on the outcome of the habitation modelling on current hydropower plant operational strategy, appropriate structural and operational mitigation measures should be explored for a more sustainable regulatory development.

The research questions for this study are as follows:

1. Evaluate the extent of hydropeaking on the lower part of the Kalajoki below Hamari HPP. Is there a need to improve ecohydraulic state of the river?
2. What is the impact of the current hydropeaking regulatory practice on the morphological structure of the rapids?
3. Using 1D hydraulic modeling such as HEC-RAS, to what extent does the hydropeaking practice affect the fluctuation in surface water elevation (WSE) downstream of the Hamari HPP. At what point does the fluctuation become very minimal?
4. Using 2D fish habitat modeling, how do the different current regulatory practices affect the quantity and quality of fish habitat at Juurikoski and Hihnalankoski.
    a. How does the current hydropeaking practice affect the location of habitat available of brown trout at Juurikoski, Hihnalankoski and modified Juurikoski?
    b. How is the fish habitat quantity improved at Juurikoski when its river structure assumes the river structure of Hihnalankoski?
    c. What is the quality of Juurikoksi, Hihnalankoski and modified Juurikoski in terms of stranding potential, changes in suitable habitat location thermopeaking on fish habitat at Juurkoksi and Hihnalankoski.

Note that usually, fish habitat models compares a specific target fish's water depth, velocity and substrate preference with modeled water depth, velocity and substrate condition of the study river reach to describe fish habitat quantity and quality available for that specific target fish. In this study, however, due to time limitation on measuring substrate of study river reaches, a perfect substrate condition was assumed for all classes of Brown trout in all study river reaches. The specific tasks for this study include but not limited to following;

1. River bed elevation measurements to generate riverbed bathymetry for 2D hydraulic modelling.
2. Set-up pressure sensors to measure water level fluctuation for model calibration of 1D and 2D model

3. Set up and calibrate one and two-dimensional hydrodynamic model at different hydropeaking discharges from Hamari HPP

Where needed to implement mitigation measures (operational or structural) to ensure sustainable regulatory development

2 DESCRIPTION OF PROJECT AREA

The study was carried out on the River Kalajoki located in the Northern Ostrobothnia region of Finland. It takes it sources from Hautaperä reservoir and exits into Bothnian Bay (northern part of the Baltic Sea) at geographic coordinates 64°17′22′′ N, 23°54′57′′ E usually discharging humic water during the high flow periods. The Kalajoki River has a drainage area of 4260 km^2 and a mean discharge of 29 m^3s^{-1} (mean maximum discharge of 246 m^3s^{-1} and mean minimum discharge of 4.1 m^3s^{-1}) (Aronsuu et al., 2015). The main tributary from the right to the Kalajoki is Vääräjoki. The major landuse types in the Kalajoki River basin are agriculture lands (most dominant), forests, and bogs. The hydrology of the Kalajoki responds very much to changes in precipitation due to its small lake percentage of 1.8%.

Figure 1 Kalajoki Basin showing the four upstream hydropower plants (HPP), gauging station and 2 study reach Juurikoski and Hihnalankoski

The Kalajoki River has a total length of 110km and a general gradient of 5.73% (100 m drop). The middle to the upper part of the Kalajoki (45-110 river kilometres [rkm]) is heavily modified. Four hydropower plants (short-term regulated hydropower plants) were built on the middle to upper reach from the 1970s to early 1980s (See figure 1 and table 1). Previously, the lower part of the Kalajoki (45 rkm) was modified to control flood and support log floating resulting in the destruction of all the natural fast flowing sections of the river (rapids). During the early 2000s, those fast flowing sections were restored to enhance habitation of the fish population including salmon, trout, lamprey, crayfish and other fish species. Ever since the start of operation of those four peaking hydropower plants at the middle to the upper part of the Kalajoki, the lower part has been experiencing hydropeaking which is creating problems for fish habitat. (Aronsuu et al., 2015).

Table 1 The four hydropower plants in the middle to upper Kalajoki in position order from down to upstream (source: Ely-Keskus Database)

Hydropower Plant (HPP)	Location	Head [m]	Capacity [MW]	Energy Generation [GWh]	Commissioning Date
Hamari	Ylivieska	6.4	2.5	7.6	1984
Padinki	Nivala	4.3	1.1	4.3	1979
Oksava	Oksava	10.5	3	8.9	1975
Hinkua	Haapajärvi	19.6	6.3	9.7	1975

Fishing of salmon and trout is prohibited from mid-September to mid-November with a minimum legal length of 50 cm for both fishes. Kalajoki has a fish population category of 6 (salmon and trout), a total of 81 hectares(ha) of fish reproduction area comprising of 42 ha in the main channel, 30 ha in Vääränjoki and 9 ha in Siiponjoki. (Pedersen, 2011).

The methods used in this study aims to quantitatively and qualitatively evaluate the effect of hydropeaking (from short-term regulated power plants) through modeling on the fish habitat of three rapids on the Kalajoki within the study reach shown in figure 1. These 3 rapids from downstream of Hamari power plant to the mouth of the river are Jurriskoski (Rapid 1) and Hihnalankoski (Rapid 2). As shown in figure 2, the

Niskankoski River gauging station is located between Haapakoski and Hihnalankoski whiles Juurikoski is located some few hundreds of meters downstream of the Hamari hydropower plant.

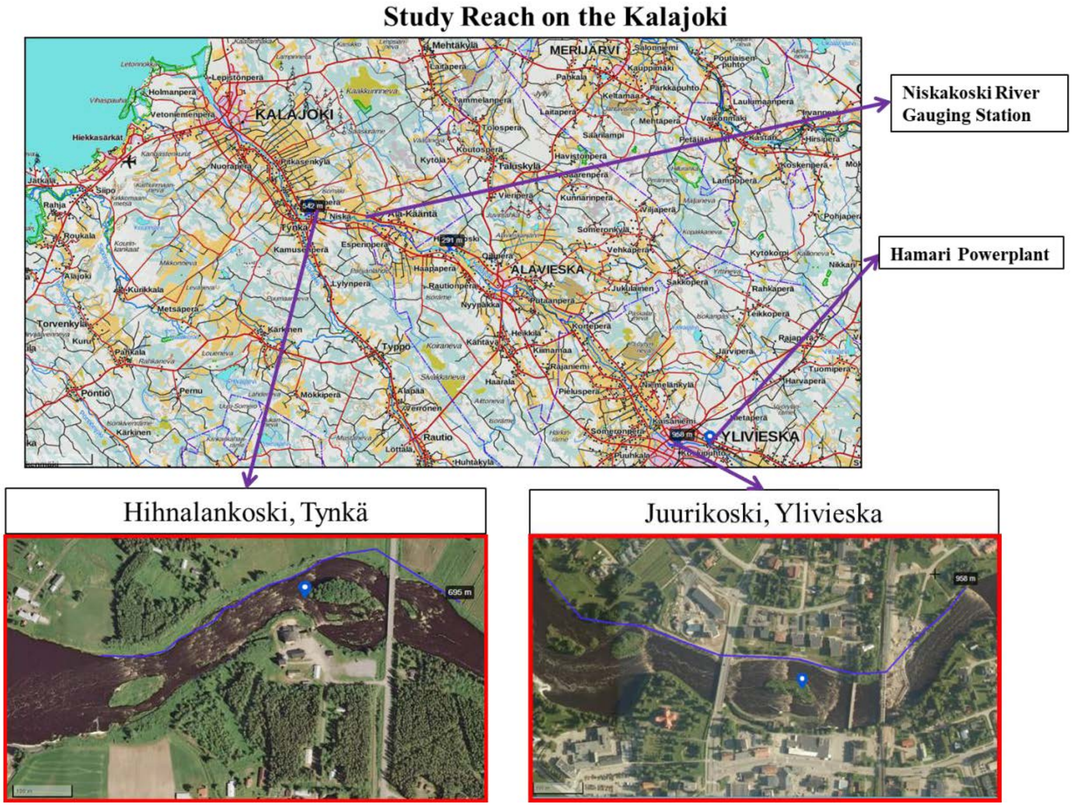


Figure 2 Study reach showing the relative positions of two rapids understudy to the Hamari hydropower plant and the Niskankoski river gauging station (map source: National Land Survey of Finland)

2.1 Juurikoski, Ylivieska

The Juurikoski spans a river distance of 545 m and has five weirs in the river reach. The naturally rapid has been totally reconstructed in the early 2000s to enhance flood control and landscape. In this study, only the four sub-rapids shown in figure 3 were considered within the model reach. Each sub-rapid had weirs which controlled the flow the rapids. The study reach had two islands. The upper-most island was located close to Weir 1 while the other island was located downstream close to Weir 4. Each of the weirs had at least a trapezoidal-shaped opening with a bottom width about 5 m. Weir 2 had 2 trapezoidal shaped openings, a width across river of about 90 m and a length in the downstream direction of about 35 m. Weirs 1B and 1A each had 1 trapezoidal shaped openings, a width across river of about 35 m and a length in the downstream direction of about 35m. Weir 3 had 2 trapezoidal shaped openings, a width across river of about 35 m and a length in the downstream direction of about 25 m. Weir 4A had 1 trapezoidal shaped opening, a width across river of about 55 m and a length in the downstream direction of about 40 m. Weir 4B had 1 trapezoidal shaped opening, a width across river of about 15 m and a length in the downstream direction of about 20 m.

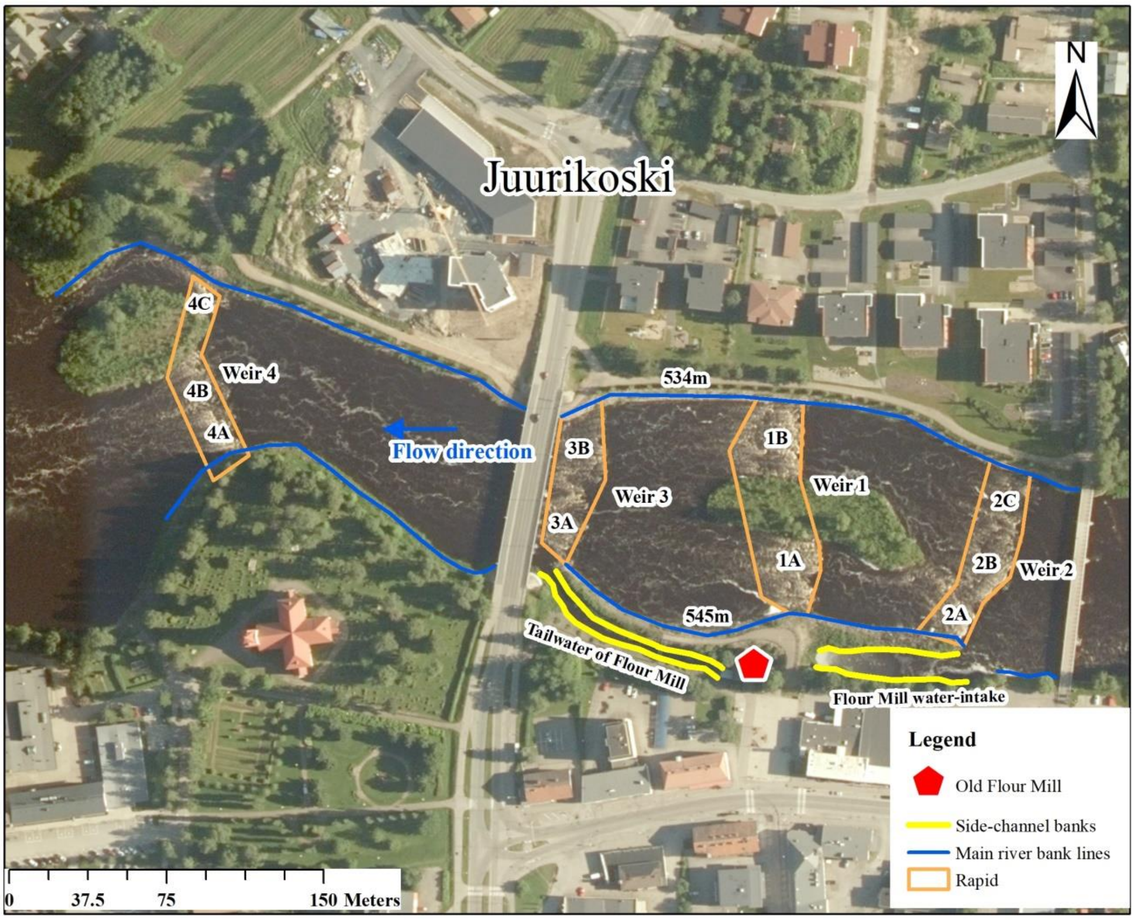


Figure 3 Detailed site description of Juurikoski, Ylivieska: Source of map National Land Survey of Finland

As shown in figure 3, the rapid Juurikoski had 4 different sub-rapids within the model reach. These rapids are labelled Weir 1 to 4 in figure 3. A side-channel exists near the left side of the main river banks (looking into the downstream direction) which sends water to and from an old Flour Mill. Note that the upstream side-channel takes water to the Mill whiles the tailwater from the Mill passes through the downstream side-channel. Since the Mill does not operate anymore, water flows freely from the upstream side-channel to the base of the Mill through a single big circular pipe (see Appendix 9) and exits the Mill through the downstream side channel (see Appendix 10).

2.2 Hihnalankoski, Tynkä

The Hihnalankoski rapid has been dredged during the early days to enhance timber floating and flood control, but it was totally restored in the early 2000s to enhance the habitat of lotic organisms including salmonids. The Hihnalankoski rapid span 180m with no weirs in the rapid area studied. The left bank of the rapid (looking in the downstream direction) had a side-channel which carried water to and out from an active flour milling plant called Tyngän Mylly. Some small amount of water from the river flows into the tailwater channel of the side-channel through small rockfill barrier.

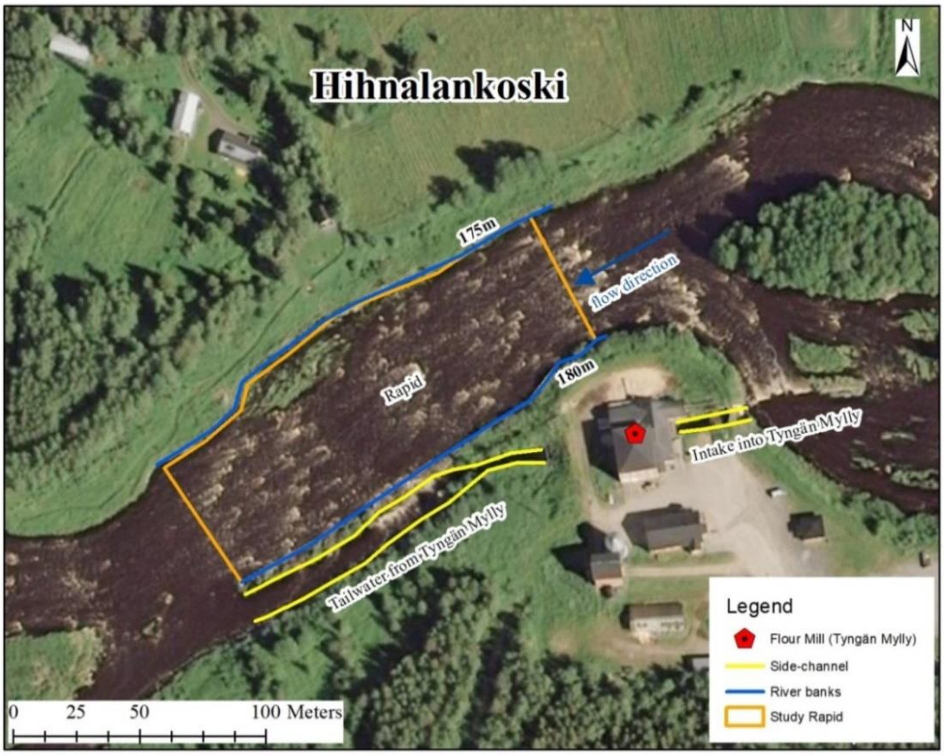


Figure 4 Detailed site description of Hihnalankoski, Tynkä: Source of map: National Land Survey of Finland

3 MATERIALS AND METHODS

3.1 Data acquisition and quality assessment

Hydrological data and assessment of average hourly discharge

Hydrological data was collected from the Environmental Information System HERTTA database. Hourly plant discharge outflow data from Hamari Hydropower Plant (station code: 5300650) was collected from **1.1.2006** to **31.12.2018.** The data was checked for abnormalities and erroneous data before sorting them out for further analysis. The average hourly discharge data from Hamari hydropower plant was computed after sorting.

Fish preference curves

The preference curves for brown trout, the target fish species for this study were acquired from the Finnish Natural Resources Institute (LUKE) as part of the data for the study. A more detailed source and description of those preference curves can be found in **chapter 3.3**

3.2 Hydropeaking classification of Kalajoki River

The level of hydropeaking on the Kalajoki River was assessed using a method based on indices developed by Carolli et al. (2015) in Ashraf et al. (2018). The method combined hydropeaking indicator (HP1) with ramping rate indicator (HP2) to define a hydropeaking class to describe the hydropeaking. According to Ashraf et al. (2018) HP1 is a dimensionless number that measures the magnitude of hydropeaking. HP1 for the i-th day could be calculated as an aggregated sum of the ratio between the difference between the maximum (Q_{max}) and minimum (Q_{min}) daily discharge to the mean (Q_{mean}) daily discharge for the i-th day as shown in equation 10. HP1 was calculated as the annual median value of the HP1 for the i-th day as shown in equation (11).

HP2 measures how fast or slow the water level is reduced or increases during hydropeaking. HP2 for the i-th day was calculated by equation (12). HP2 was computed as the annual median of daily values of $HP2_i$ which represents the 90^{th} percentile of the discretized time derivative of the instantaneous stream-flow series (see equation 13 and 14). k refers to available discharge datum.

$$HP1_i = \frac{Q_{max,i} - Q_{min,i}}{Q_{mean,i}} \qquad i \in [1,365] \tag{10}$$

$$HP1 = median\left(HP_i\right) \tag{11}$$

$$\left(HP2_k\right)_i = \left(\frac{\Delta Q_k}{\Delta t_k}\right) = \left(\frac{Q_k - Q_{k-1}}{t_k - t_{k-1}}\right)_i, \quad i \in [1,365] \tag{12}$$

$$HP2_i = P_{90}\left|\left(HP2_k\right)_i\right| \tag{13}$$

$$HP2 = median\left(HP2_i\right) \tag{14}$$

Hydropeaking thresholds were set for HP1 and HP2 as TR_{HP1} and TR_{HP2}. TR_{HP1} and TR_{HP2} were computed based on equations (15) and (16) respectively according to Carolli et al. (2015)

$$TR_{HP1} = P_{75}\left(HP1_i^{unp}\right) + 1.5\left(P_{75} - P_{25}\right)\left(HP1_i^{unp}\right) \tag{15}$$

$$TR_{HP2} = P_{75}\left(HP2_i^{unp}\right) + 1.5\left(P_{75} - P_{25}\right)\left(HP2_i^{unp}\right) \tag{16}$$

where

$HP1_i^{unp}$ *and* $HP2_i^{unp}$ *are the daily values for the two indicators for unpeaked stream gauges*

P_{75} *and* P_{25} *are the* 75^{th} *and* 25^{th} *percentile for the distribution*

Four pressure classes namely 1, 2, 3 and 4. **Class 1 and 3** was designated **medium impact**. **Class 2** (**low impact**) and **Class 4** (**high impact**). As described by Carolli et al. (2015) the developer of the methodology, the mathematical description of the classes and their hydropeaking impact description are shown below :

$$
\begin{aligned}
&Class\ 1: HP1 < TR_{HP1}\ and\ HP2 < TR_{HP2} && \Rightarrow\ medium\ impact\\
&Class\ 2: HP1 > TR_{HP1}\ and\ HP2 < TR_{HP2} && \Rightarrow\ low\ impact\\
&Class\ 3: HP2 > TR_{HP2}\ and\ HP1 < TR_{HP1} && \Rightarrow medium\ impact\\
&Class\ 4: HP1 > TR_{HP1}\ and\ HP2 > TR_{HP2} && \Rightarrow\ high\ impact
\end{aligned}
$$

3.3 Preference curves of brown trout

Preference curves for brown trout were acquired from (Mäki-Petäys, 2001) from the Finnish Natural Resources Institute Finland (Luke) in Oulu as part of the data needed for the project. Note brown trout is called Taimen in Finnish. These preference curves include velocity and depth preference curves for brown trout size <10 cm, 10-15 cm and >15 cm. Substrate preference was not measured in this study and hence was set to 1 (most suitable) for all substrate sizes for the sake of modeling in the River 2D model since it's an important input to the fish habitat model. The depth, velocity and substrate preference curves for different length of brown trout are shown in figures 3, 4 and 5. A tabular data for preference curves is shown in Appendix 1, 2 and 3. The velocity and depth habitat preference curves for Brown trout under 10 cm were made from combining preference values for six rivers in Finland namely; Astervajoki, Koitajoki, Kutinjoki, Kuusinkijoki, Loukusanjoki and Varisjoki. The velocity and depth habitat preference curves for brown trout from 10 to 15 cm were made from the combination of preference values from Astervajoki, Koitajoki, Kuusinkijoki, Loukusanjoki and Rutajoki whiles those for brown trout over 15 cm were made from combining the preference values from Koitajoki, Kuusinkijoki, Rutajoki, and Varisjoki.

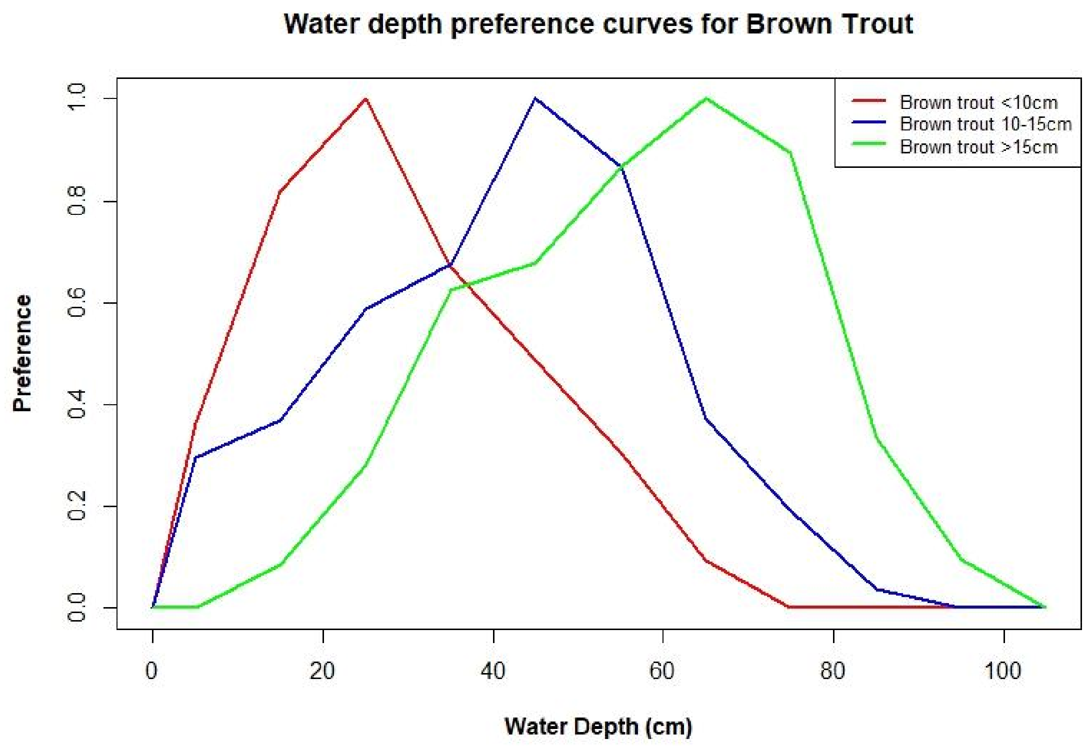


Figure 5 Depth preference for brown trout

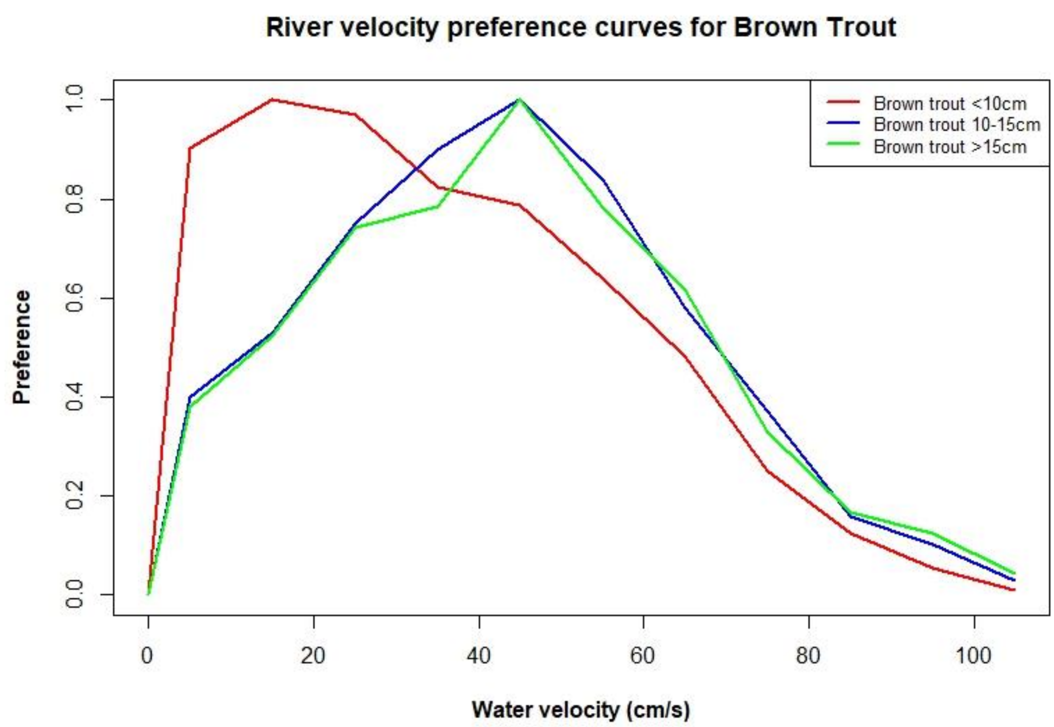


Figure 6 Velocity preference for brown trout

3.4 Field observation

Juurikoski

A visual inspection was carried out on the 4 rapids in the Juurikoski during the allowable 2.5 m^3/s minimum flow from the Hamari hydropower plant typically at around 7:00 am. A photograph showing the physical appearance of the rapids during the current minimum flow of 2.5 m^3/s in the Kalajoki are shown in appendix 4 to 8. Appendix 4 shows pictures of rapids 2A, 2B and 2C. Appendix 5 shows pictures of rapids 3A and 3B. Appendix 6 shows a picture of rapid 1B. Appendix 7 show pictures of rapids 4A and 4B. Appendix 8 shows a picture of rapid 4C.

The entire rapids during current minimum flow looked dry showing unsubmerged moss and algae in the rapid. According to the view of Mr Olli van der Mer (an expert in fish biology and habitat modeling and a partner during site inspection and data collection), the substrate sizes of all rapids looked good for brown trout as they ranged between 0.7 and 1 suitability. However, the water depth and velocity on the rapid at minimum flow doesn't seem to provide any habitat for brown trout at all stages of development. No obvious nursery sites for brown trout was found during a walk through the study reach from rapids 1 to 4. The side channel going through the old Flour Mill seemed to be a good place for a fish nursery but would need to be confirmed through modeling. According to previous information during the time of constructing the weirs in Juurikoski, the pools were left without any large stones (substrate) and hence very deep not good substrate suitability for all brown trout classes studied in this work.

Hihnalankoski

Prior to and during riverbed elevation measurements at Hihnalankoski, the conditions of rapid and substrate were inspected to get an impression of how successful the constructed rapid at Hihnalankoski had been in supporting fishes habitat conditions. By visual inspection, as shown in appendix 11, the entire rapid was well covered with water during the whole time riverbed measurements were surveyed and looked good for fishes. The river had lots of clean moss which are a food source for fishes (see Appendix 12).

On many occasions, fishes were spotted jumping in Hihnalankoski especially in the pools areas, unlike Juurikoksi. Newly hatched fishes were seen at Hihnalankoski during field visit near the river banks (See Appendix 13). In general observation of rapids and substrate looked for fishes. The tailwater water from the Tyngän Mylly had no influence on river reach studied in Hihnalankoski.

3.5 Field measurements

Riverbed and water surface elevation measurements

The river bed elevation measurements were done with the Javad Triumph-2 GPS with real-time kinematic technique (RTK) and accuracy of 1-2 cm. More about this equipment can be found on (Javad, 2017). Point measurements of river bed elevation on the rapids and river banks were taken in spacing of about 20 to 50 cm depending on the homogeneity or heterogeneity of the river bed. A spacing of 2 m or a little more was used for river bed sections which were more monotonous or homogenous whiles 50 cm or smaller space distances were used for river bed sections which were more heterogeneous. This was done to minimize the resulting errors the bed surface mesh generated for the hydraulic modeling. The River bed elevations in the pools were sub-contracted to Mitta Oy Company in Finland simply because of the difficulty of measuring river bed elevation in the pool with the Javad Triumph-2 GPS. The Sontek-M9 River discharge, bathymetry and current profiling equipment mounted on a remote-controlled boat was used to measure river bed elevation in the pools. The space between transects in the pools was 5 to 10 m since the pools were homogeneous. The water surface elevations were either measured instantaneously with the Javad Triumph-2 GPS or continuously at set time spacing with the ***Solinst Levelogger model 3001***. More about this equipment can be found on (Solinst, 2019).

Hihnalankoski

A total of 6957 single GPS points of riverbed elevation were measured at Hihnalankoksi. Since the river structure of Hihnalankoski had no too deep pools, the Javad Triumph-2 GPS was used throughout to take riverbed elevation in a dense manner with a spacing of 20 to 50 cm between points. The surface water elevation at Hihnalankoski was measured at 5 locations shown in figure 8.

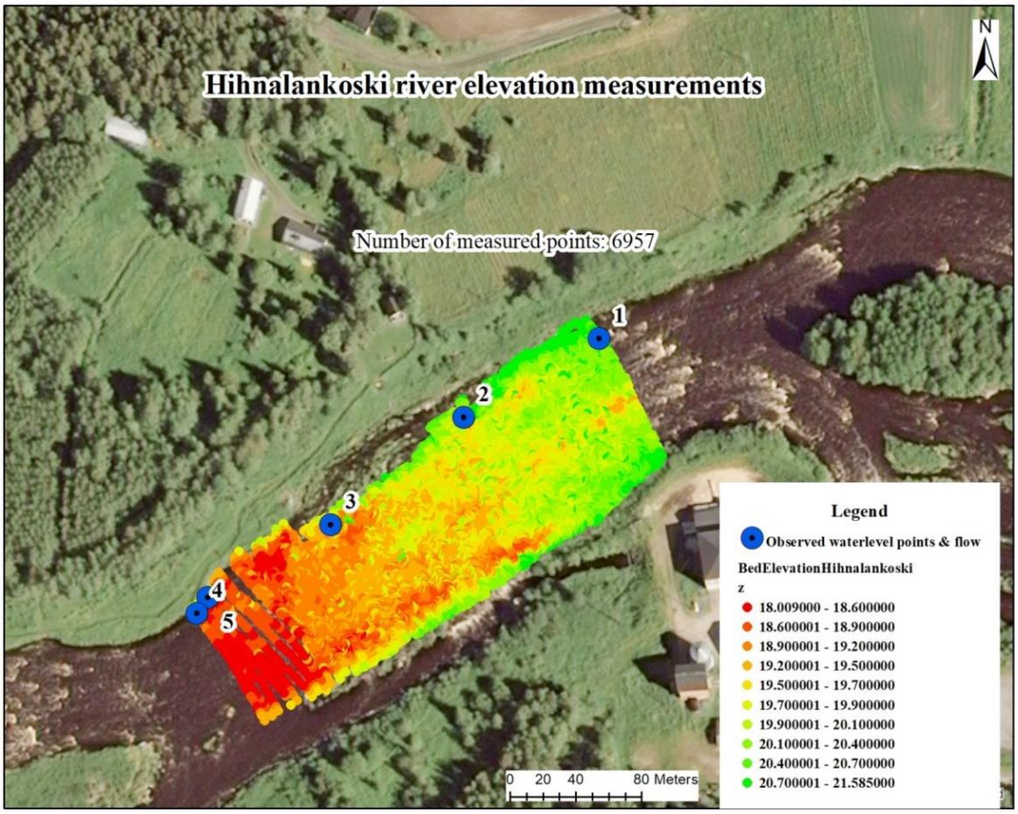


Figure 7 Riverbed elevation measurement at Hihnalankoski showing positions where observed water levels were measured

Juurikoski

A total of 19780 single GPS points of riverbed elevation were measured. Those 19780 points cover the shallow areas around the weirs, the river banks and the islands. The deeper pools were measured with mini-boat mounted eco-sounding equipment mounted with a spacing of 5 to 10 m between transects. The WSE at 5 points measured at 5 locations covering uniformly the entire river reach at Juurkoski.

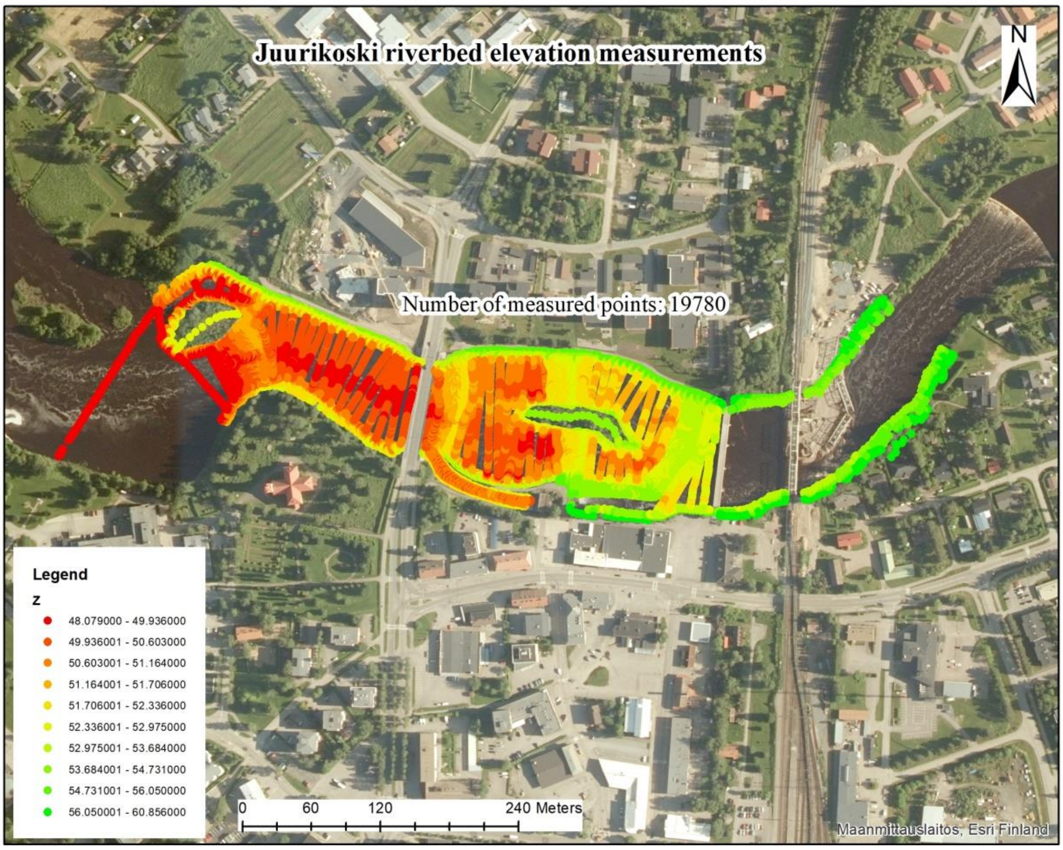


Figure 8 Riverbed elevation point measurements at Juurikoski

3.6 Selection of typical hydropeaking discharges in Kalajoki from Hamari hydropower plant

In order to select typical hydropeaking discharge in a day from current practice and water use in the lower part of the Hamari hydropower plant, daily average discharge from current dates (20015 to 2018) was selected. For each year, daily average discharges of open water season typically from 15th May to 15th October were selected to match the fish preference curves used in this research. The daily average discharges for open water period for all year from 2015 to 2018 were combined to form one continuous time series of discharge data. The data were sorted from highest to lowest and ranked from highest to least discharge where the highest discharge had a rank number 1. A probability of exceedence for each ranked discharge was computed using the Gumbel equation shown in equation 16.

$$P = \left(\frac{M}{n+1} \right) * 100\% \tag{16}$$

where

P is probability of exceedence of a given discharge (% time)

M is the ranked position of each sorted discharge (dimensionless)

n is the number of events for the period of data record of the rank number of the least sorted discharge (dimensionless)

Ten (10) dates each were selected for the ranked daily average discharges with a mean of 15.3 m^3/s (representing 24-26 % probability of exceedence), 5.92 m^3/s (representing 49-51 % probability of exceedence) and 3.5 m^3/s (representing 79-81 % probability of exceedence). The ten selected dates for each average mean daily discharge were plotted together and one date hydrograph showing typical hydropeaking selected for 15.3, 5.9, and 3.5 m ^{3}/s as respectively shown in Appendix 14, 15 and 16. The hydrograph of the selected date can be seen in figure 10. The actual flow values for the three selected dates can be seen in Appendix 17.

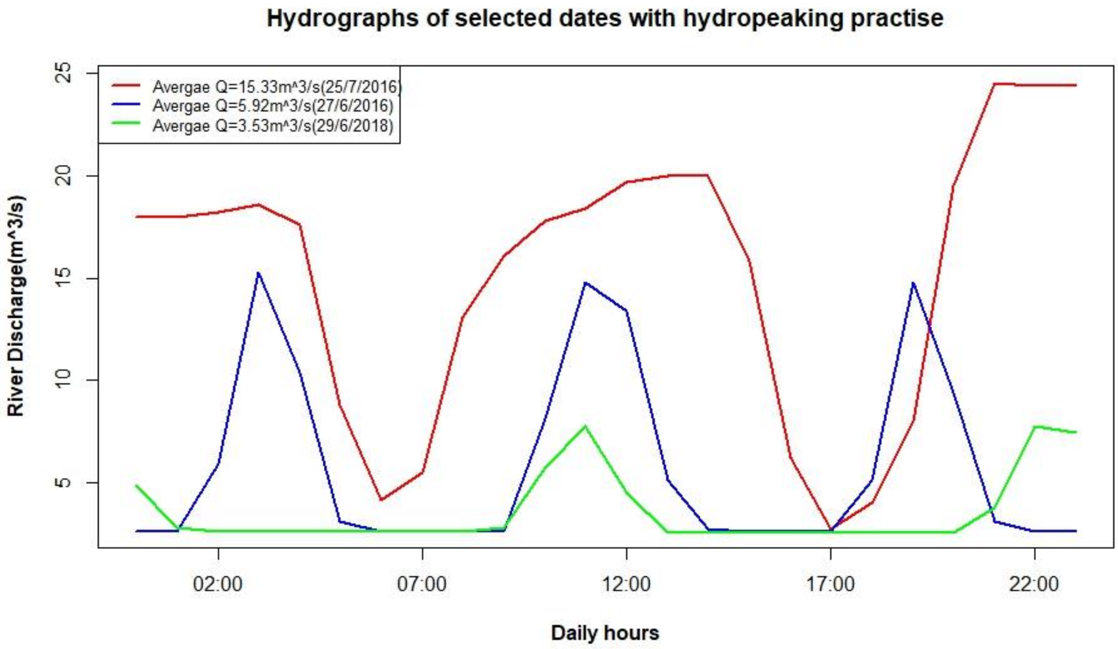


Figure 9 hydrograph of the selected dates with hydropeaking from Hamari hydropower plant

3.7 Assessment of hydropeaking induced water surface elevation fluctuation on the Kalajoki from Juurikoski to the mouth of the Kalajoki

Hydropeaking induced fluctuations in surface water level on the Kalajoki was assessed along the river stretch from just the downstream of Hamari hydropower plant in Ylivieska to the mouth of the Kalajoki near the downtown of Kalajoki city. The essence of this task was to ascertain the extent to which water surface ramps up and down due to the hydropeaking operation of the Hamari hydropower plant. A 1D model of the Kalayoki was built to easily help analyze the effect of hydropeaking on the water surface level fluctuations on the lower part of the Kalajoki. Hydrological Engineering Center's River Analysis System (HEC-RAS) model (version 5.0.7) was used to build a 1D unsteady flow model for the lower part Kalajoki. As shown in figure 10 below, the lower part of the Kalajoki spans approximately 45km from the Hamari Hydropower Plant. The following sub-chapters describe the conceptual model layout of the 1D HEC-RAS model, the required data and source, and the calibration and validation of the model.

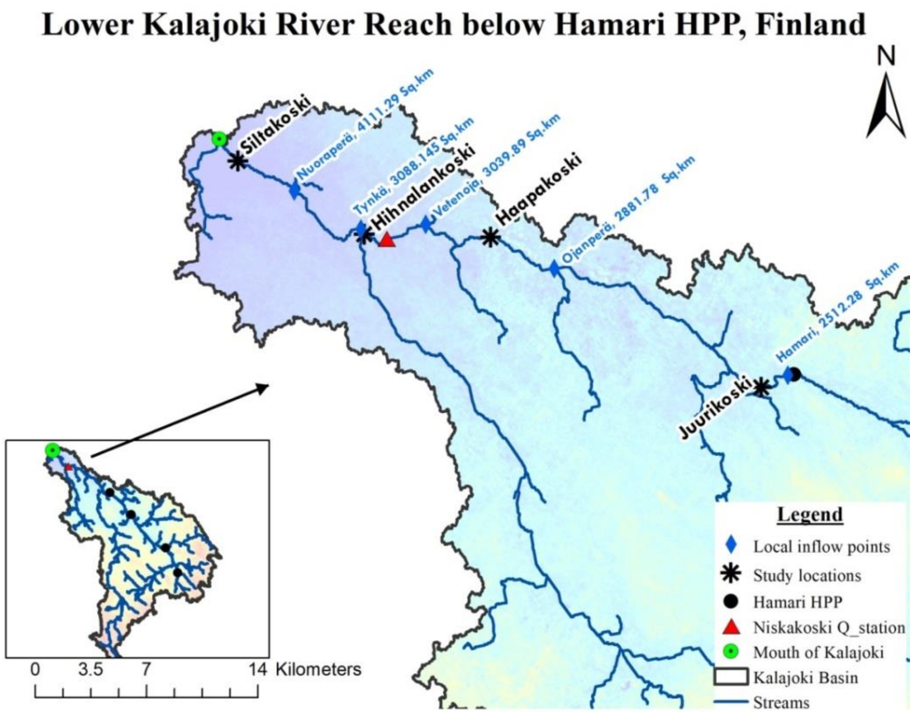


Figure 10 River reach from Hamari to outlet modeled in the HEC-RAS 1D

Conceptual model layout

The mass balance concept was used to define conceptually the model layout for the lower part of Kalajoki. Evapotranspiration was ignored in the model layout because its minimal in Finland. As shown in figure 12, the conceptual model was divided into 4 major parts connected in series beginning from Hamari Power Plant to the Gulf of Bothnia. Each part had a local inflow which was scaled from a nearby unregulated catchment in the upper part of the Kalajoki catchment. All local inflows were scaled from Tujuoja gauging station based on the assumption of similar specific runoff. Thus based on catchment area of Tujuoja and local catchment defining the local inflow for any part of the 4 parts. The discharges of those local inflows were computed simply because they are not gauged hydrologically. The next sub-chapter describes the data required and the source where those data were collected.

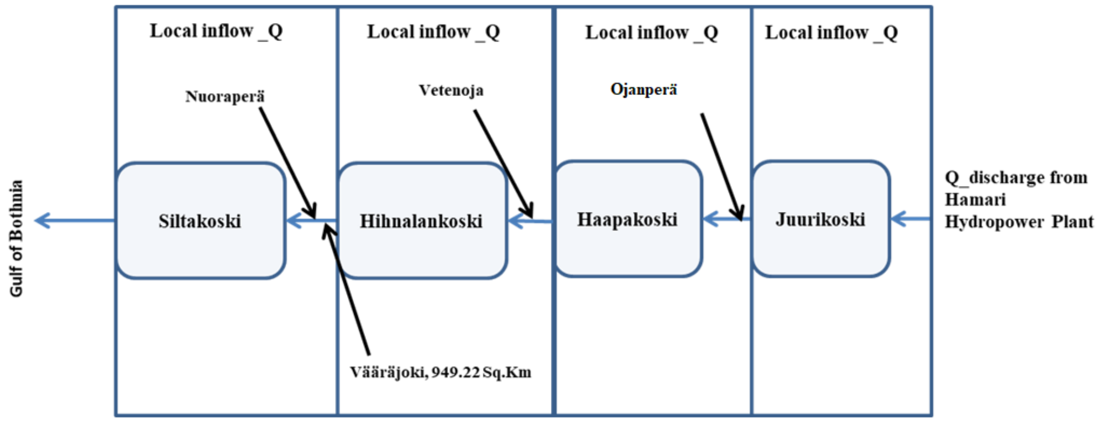


Figure 11 Flow chart showing the layout of the 1D model

Required data and source of data collection

The data required for this study was discharge data, water levels data in the Bothnia Sea close to the mouth of the Kalajoki, and observed River Water Surface Elevation (WSE) at defined points along the length of the river stretch for calibration and validation of the model. The discharge data for Hamari, Tujuoja, and Rautio were collected from SYKE’s database. Since there was no water level measuring station at the mouth of the Kalajoki, therefore the average of the hourly sea level variation data for the Baltic sea from Raahe Lapaluoto and Pietarsaari Leppäluoto were used. These data were collected from the Finnish Meteorological Institutes (FMI) database (FMI, 2019a) originally in theoretical mean sea level and converted into N60 elevation system based on the guidelines from the FMI in (FMI, 2019b) for the year 2019. Kalajoki's surface water variations along the river was measured with a Solnist Level logger and barologger at six cross-sections with a distance of approximately 7 to 7.5km between successive cross-sections. The level loggers were placed at locations good enough and not dangerous for the person installing the device as some parts of the river were very muddy and deep and could threaten the life of the installer of the devices. The next chapter explains details about the 1D HEC-RAS model, how each sub-part of the was defined into the model

HEC-RAS 1D Model, model set up, input parameters, boundary conditions

This chapter highlights model set up, input parameters, boundary conditions. All local ungauged local inflow were bunched up together into single flow hydrograph from Ojanperä, Vetenoja, and Nuoraperä and defined into the 1D HEC-RAS model at river cross-sections (XS) 22000, 15300, and 3400 respectively as lateral inflows. The discharge from the Hamari Hydropower Plant was defined in the model as the upper or beginning boundary condition at XS-45240. The average of the seawater level variation from Raahe Lapaluoto and Pietarsaari Leppäluoto were defined into the model at the lower boundary condition. Since the 1D model does not begin at the sea, the water level measurements were adjusted based on an observed average slope at XS-0 as defined by the model and the average sea level measured at Raahe Lapaluoto and Pietarsaari Leppäluoto. The adjustment is illustrated in figure 13. In summary, 19.6 cm was added to all computed average water levels between measurements Raahe Lapaluoto and Pietarsaari Leppäluoto to get the correct water levels at the lower boundary condition of the 1D HEC-RAS model.

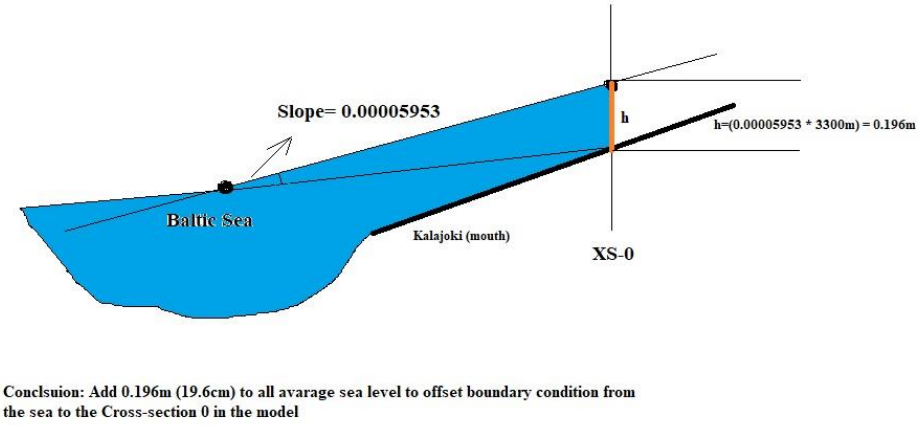


Figure 12 A schematic diagram showing the correction at the lower boundary condition

Calibration and Validation of the model

After completion of the setup of the 1D model, it was calibrated and validated on the observed water at cross-sections (SX) 37600, 29000, 21800, 14200, 7700, and 900 measured during high, medium and low flows to test and ensure the robustness of model for the test flows in this study. The results of the observed high calibration and observed medium and low validation are shown in figures 14, 15 and 16 respectively. The calibrated observed data on high flow was measured on 18th to 19th September 2019. The observed data for medium flow validation was measured 14th September whiles that for the low flow was measured on 22nd August 2019. The calibration of the model was done by adjusting the roughness of the river bed to get the best match between observed and modeled surface water elevation. After completion of the calibration, the model was verified or validated with water surface elevations (WSE) on medium and low flows. The goodness-of-fit of the observed and modeled WSE were compared with ***Normal correlation***, ***Pearson coefficient***, ***Mean absolute error (MAE)***, ***Root mean squared error (RMSE)*** and ***Nash-Sutcliffe efficiency (NSE)***. The values of goodness-of-fit of the model for calibration and all validations are shown in table 2 below.

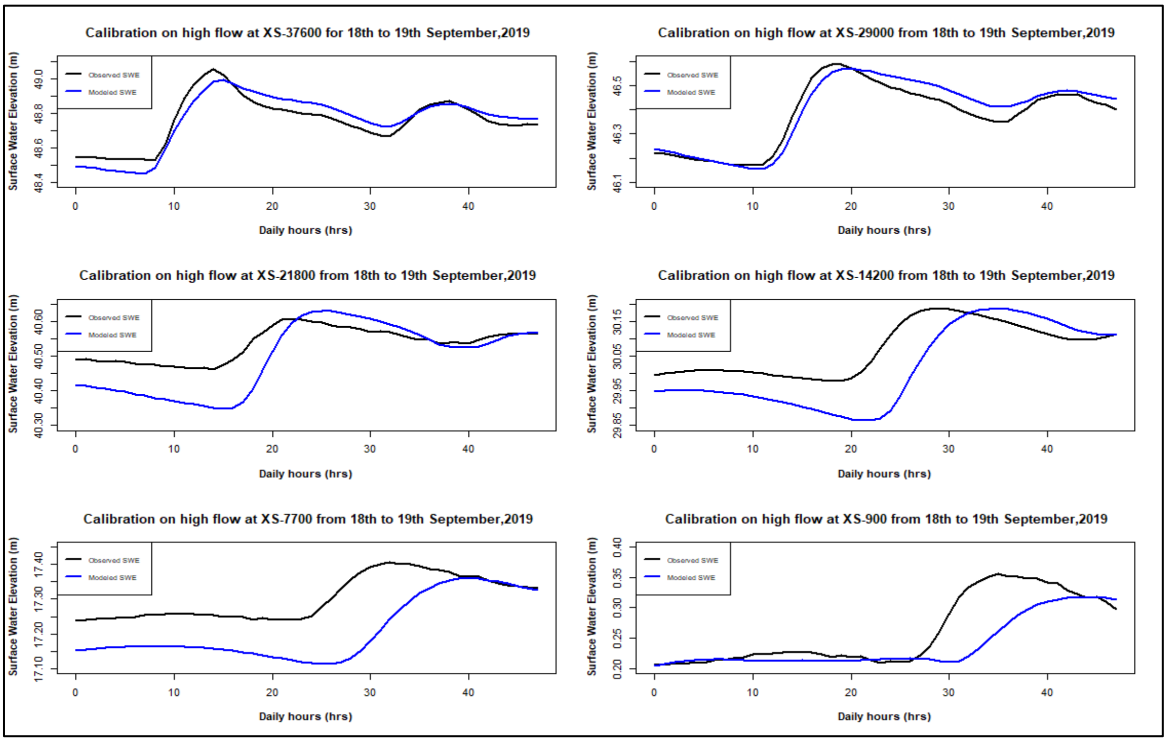


Figure 14 Results of calibration of the 1D model on observed high flow scenario

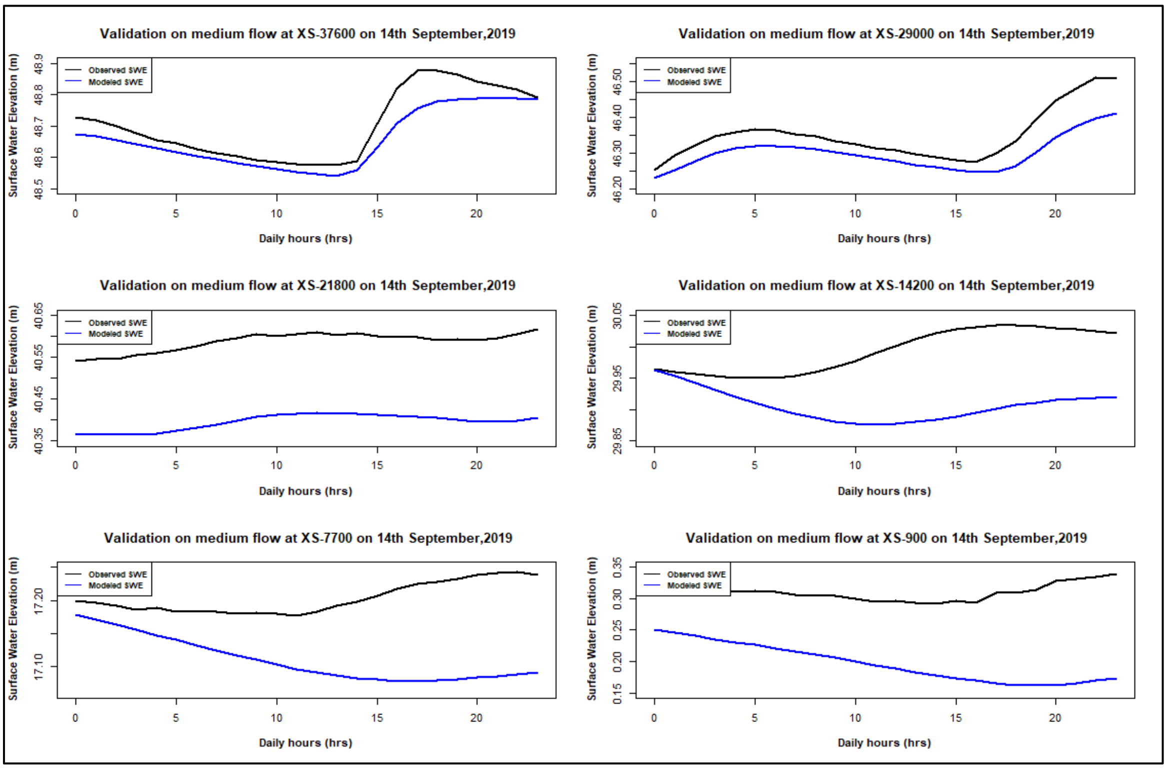


Figure 15 Results of validation of the 1D model on observed medium flow

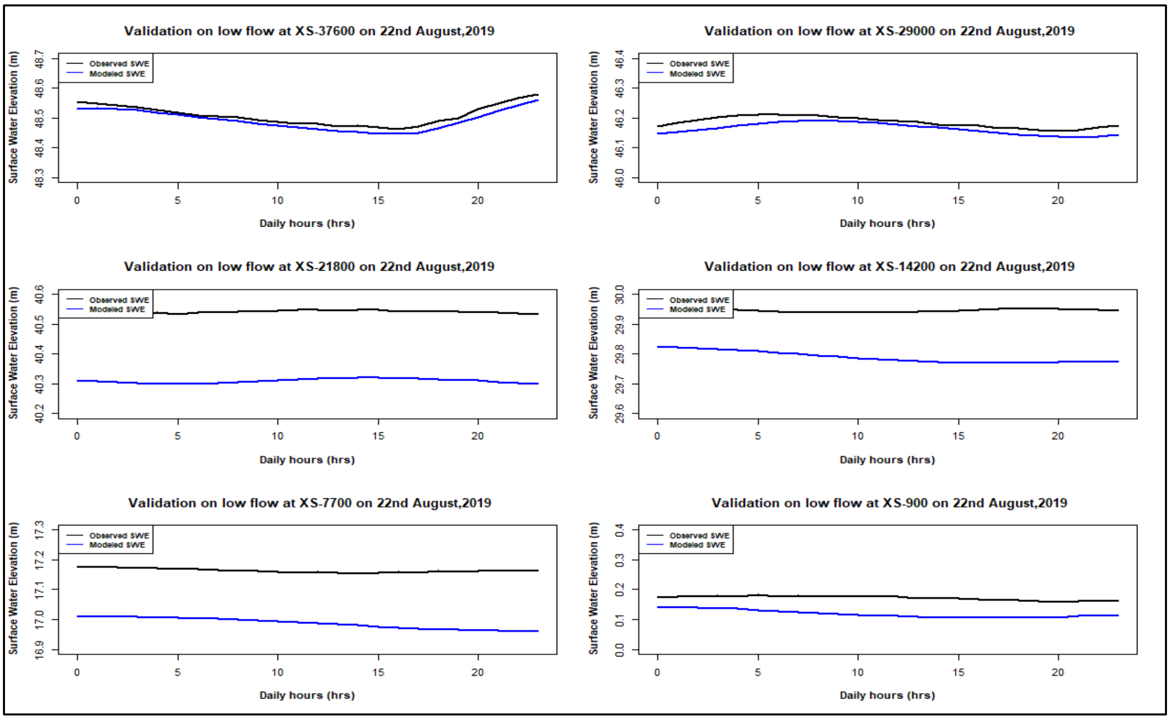


Figure 16 Results of the validation of the 1D model on observed low flow

Table 2 Results of goodness-of-fit between modeled and observed WSE after calibration and validation of the 1D HEC-RAS model

Goodness-of-fit parameters	XS-37600	XS-29000	XS-21800	XS-14200	XS-7700	XS-900	Scenario
Correlation	0.940	0.964	0.928	0.811	0.722	0.786	High flow calibration
Pearson	0.940	0.964	0.928	0.811	0.722	0.786	
RMSE	0.054	0.040	0.070	0.089	0.111	0.042	
NSE	0.845	0.906	-1.239	-0.431	-2.276	0.461	
MAE	0.049	0.033	0.055	0.072	0.093	0.025	
Correlation	0.970	0.965	0.937	-0.243	-0.519	-0.017	Validation on medium flow
Pearson	0.970	0.965	0.937	-0.243	-0.519	-0.017	
RMSE	0.054	0.058	0.192	0.980	0.105	0.118	
NSE	0.746	0.298	-74.556	-7.456	-20.137	-78.151	
MAE	0.045	0.051	0.192	0.086	0.093	0.113	
Correlation	0.980	0.904	0.775	0.204	0.686	0.654	Validation on low flow
Pearson	0.980	0.904	0.775	0.204	0.686	0.654	
RMSE	0.018	0.023	0.231	0.158	0.177	0.054	
NSE	0.723	-0.599	-1856.314	-914.198	-839.554	-59.068	
MAE	0.016	0.021	0.231	0.157	0.177	0.053	

Note: XS- means River Cross Section

The calibration of the 1D hydraulic models was a very important task for this field study to confirm the reliability of the models. The 1D model calibration presented challenges which needed special attention and time to overcome. The 1D model was initially calibrated on high flows and validated on low and medium flows. The results of the validation showed much lower simulated WSE the observed WSE for both low and medium flow validation. The poor validation of WSE at low and medium during high flow calibration informed the decision to perform a low flow WSE calibration and validation at high and medium flow. The results showed a much higher simulated WSE than the Observed WSE at medium and high flow. It was clear that for the same model, higher manning or river bed roughness numbers were required for low flow calibration whiles much lower manning numbers were required for high flows. Based on the result of the calibration, a final decision was made to have two separate calibrations for the high and low flow scenarios in order to have reliable results for the various hydropeaking flow scenarios for this study. Low and medium hydropeaking flow due to their similarity in terms of discharge magnitude were modelled with ***low flow calibrated 1D model*** whiles the high hydropeaking flow scenario was modelled with ***high flow calibrated 1D model***. The robustness of the 1D HEC-RAS model was tested during extremely high WSE variation during late summer 2019. A model was used to simulate WSE and discharge variation from 20th to 24th October 2019. The variation in WSE at the defined cross-sections were put in boxplot for further analysis. Similarly, the observed WSE variation at Niskakoski was then compared to have an impression of model reliability for larger flows outside the three test discharges.

3.8 Juurikoski 2D hydraulic and fish habitat modeling

The 2D hydraulic modeling and fish habitat simulation of 534 m stretch of Juurikoski was modeled in River 2D. The river bed topography of Juurikoski was surveyed with GPS in RTK for the shallow areas near the weirs whiles the pools were measured with GPS with depth sounder device in a little boat. The elevations measurements from both GPS (see figure 14a) and depth eco sounder devices (See figure 14b) were combined to generate a TIN mesh for the Juurikoski river bed with the help of the **River 2D bed sub-model**. The following sub-chapters outline details of the methodology used in the 2D hydraulic and fish habitat modeling of Juurikoski.

Figure 13 (a) GPS measurements in weirs and (b) Eco sounder measurements

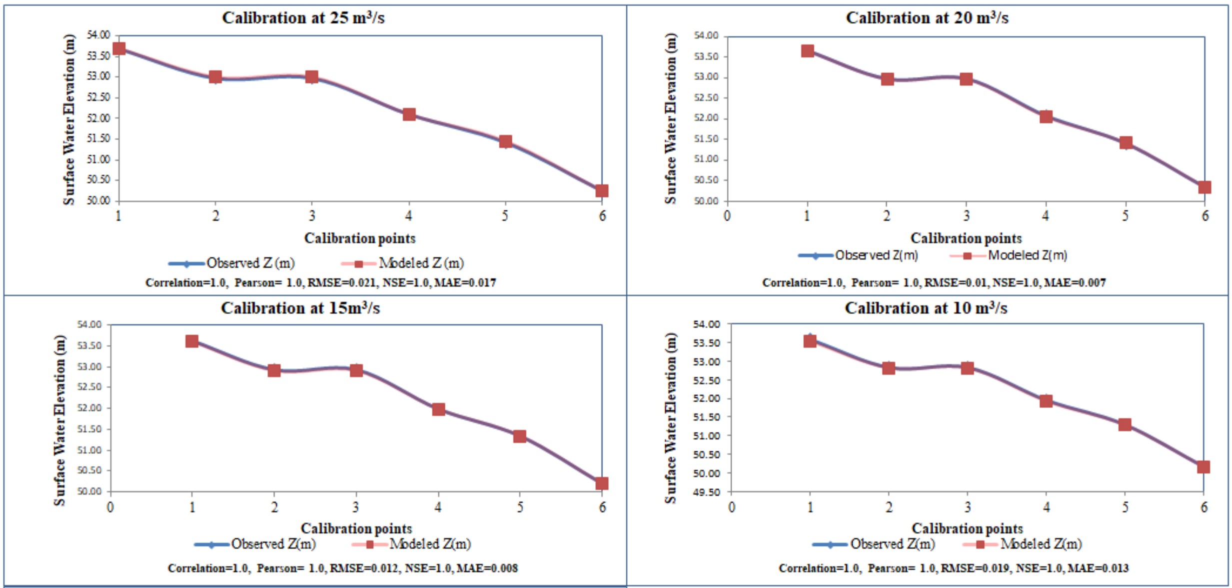
Boundary conditions, calibration and validation of hydraulic modeling

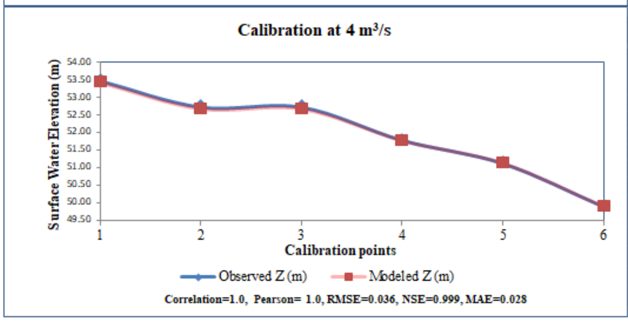
The 2D Juurikoski hydraulic model required two boundary conditions namely upper and lower boundary conditions. The upper boundary condition was at the river cross-section at the beginning of the model reach whiles the lower boundary condition was located on the river cross-section at the end of the model reach. The upper boundary condition was the discharge from the Hamari HPP and the water surface elevation at the river cross-section at the beginning of the model reach. The water surface elevation at the river cross-section at the end of the model reach was set the lower boundary condition. Steady flow analysis was run for each and every typical summer hydropeaking test discharge in the model. After the initial set-up, calibration and validation followed.

Water surface elevations (WSE) at 5 points covering uniformly the model reach were collected with a GPS. Water surface elevation were measured at those 5 points for 25, 20, 15, 10 and 4 m^3/s discharges released fairly steadily from the Hamari HPP located just about 2.1 km upstream of the model area. Each discharge was fairly kept steadily for 3 hr and WSE measurement taken after the first hour to ensure steadiness in water levels due to the effect of the target discharge released from the Hamari HPP. The model was calibrated for each of the 5 target discharges from the Hamari HPP due to the heavy modification of the Juurikoski and the exclusion of a side-channel which took a significant amount of water from the input discharge especially at the low discharges. There was no direct validation of the model but coincidentally, WSE at 20 m^3/s the 5 points verified the calibration at 25 m^3/s. After the calibration, the test discharges were combined to form one single hydrograph without repeated discharges. All test discharges from 18 to 25 m^3/s were simulated with the 25 m^3/s calibrated Juurikoski model. All test discharges from 13 to 17 m^3/s were simulated with the 15 m^3/s calibrated Juurikoski model. All test discharges from 7 to 12 m^3/s were simulated with the 10m^3/s calibrated Juurikoski model. All test discharges from 6 to 2.5 m^3/s and less were simulated with the 4 m^3/s calibrated Juurikoski model. The results of the goodness of fit between simulated and modeled WSE for the target discharges can be seen in figure 15. The ranges for specific calibrated Juurikoski models were subjectively selected to ensure plus or minus 2 to 3 m^3/s for the calibrated discharge. The lower discharges below 2 m^3/s were simulated with the 4 m^3/s calibrated Juurikoski model since that was the lowest possible calibrated Juurikoski model

Fish habitat simulation at Juurikoski

The fish habitat simulations for the three classes of Brown trout were modeled. These Brown trout classes were those sizes under 10 cm, between 10-15 cm and those sizes over 15 cm. The Fish habitat available was computed in terms of weighted usable area (WUA) and converted into 100 m per reach to allow for easy comparison between other rapid or same rapid with different scenarios. The results from calibration and fish habitat simulated are shown in chapter 4.





	Q=25m³/s		Q=20m³/s		Q=15m³/s		Q=10m³/s		Q=4m³/s	
Calibration points	Obs. Z (m)	Mod Z (m)	Obs. Z (m)	Mod Z (m)	Obs. Z (m)	Mod Z (m)	Obs. Z (m)	Mod Z (m)	Obs. Z (m)	Mod Z (m)
1	53.68	53.69	53.66	53.66	53.62	53.61	53.58	53.54	53.48	53.43
2	52.97	53.00	52.98	52.97	52.93	52.91	52.83	52.82	52.73	52.68
3	52.97	53.00	52.98	52.97	52.93	52.91	52.83	52.82	52.73	52.68
4	52.10	52.10	52.08	52.06	51.99	51.99	51.95	51.93	51.79	51.78
5	51.42	51.45	51.41	51.41	51.34	51.34	51.29	51.29	51.13	51.13
6	50.25	50.25	50.34	50.34	50.20	50.20	50.17	50.17	49.89	49.90
Correlation		1.000		1.000		1.000		1.000		1.000
Pearson		1.000		1.000		1.000		1.000		1.000
RMSE		0.021		0.01		0.012		0.019		0.036
NSE		1		1		1		1		0.999
MAE		0.017		0.007		0.008		0.013		0.028

Figure 14 Goodness of fit after calibration for the 5 target discharges at Juurikoski

3.9 Hihnalankoski 2D hydraulic modeling and fish habitat simulations

A 175 m stretch of Hihnalankoski was hydraulically modeled and its fish habitat simulated with River 2D software. Data requirement for 2D hydraulic modeling of Hihnalankoski were **river bed elevation** for generating the surface of river bed, **surface water elevation** within the modeled reach for calibration and validation of the model, and water elevation at start and end of model reach for various discharges to complete 2D hydraulic simulation. The mesh generation model took all the river bed elevation points and made Triangulated Irregular Network (TIN) mesh to represent the bathymetry of the river to help model the hydraulic of the river in 2D. The procedure for fish habitat simulation continued right after the hydraulic model simulation was completed. The data requirement for fish habitat simulation was preference curves for various classes of brown trout and river bed or channel index data. In this study, only preference curves and not fuzzy logic was used for brown trout under 10 cm, between 10 and 15 cm and over 15 cm.

Boundary conditions, calibration and validation of hydraulic modeling

Two boundary conditions were defined in the 2D hydraulic model. Water elevation at the starting and end cross-section of the river was specified as the upper and lower boundary condition respectively for each test discharge in steady flow analysis. Due to faulty Niskakoski gauging station, the inflow into the model was acquired from the 1D HEC-RAS model for the entire 45 rkm stretch. The water elevation in Hihnalankoski was manual measured with and GPS and continuously measured with Solnist pressure loggers. The Hihnalankoski 2D hydraulic model was calibrated and validated on 6.78 m^3/s and 10.3 m^3/s respectively. The results of the calibration and validation of Hihnalankoski are shown in table 3.

Development of rating curve for test discharges at Hihnalankoski

Rating curves shown in figure 15 was made for the start and end of the 2D Hihnalankoski model to help minimize the error between the WSE from the Observed and 1D HEC-RAS model. Thus the discharges from the 1D model and Observed discharges were combined in the same time domain to develop rating curves for the start and end of the model. The mathematical relationships between the WSE and discharges (Q) are shown in figure 15.

Table 3 Calibration and validation results at Hihnalankoski

Positions	**Calibration(6.78m³/s)**		**Validation(10.3m³/s)**	
	WSE(Obs)	WSE(modeled)	WSE(obs)	WSE(modeled)
point 1	20.53	20.53	20.65	20.65
point 2	20.33	20.33	20.39	20.41
point 3	20.13	20.14	20.19	20.2
point 4	19.52	19.56	19.61	19.65
point 5	19.13	19.15	19.23	19.23
point 6	19.15	19.15	19.24	19.23
point 7	19.11	19.11	19.2	19.2
Correlation	1		1	
Pearson	1		1	
RMSE	0.02		0.02	
NSE	1		1	
MAE	0.01		0.01	

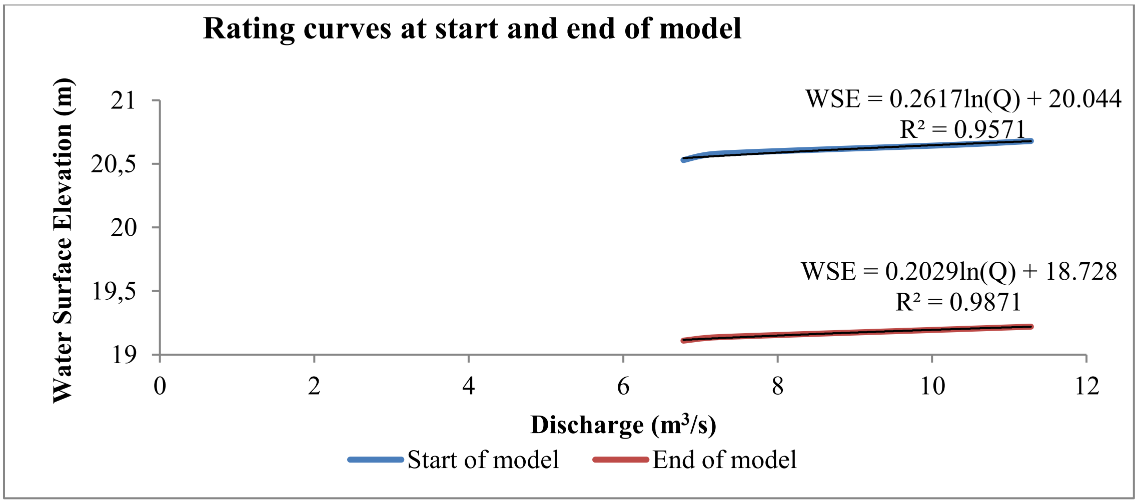


Figure 15 Rating curves for the start and end of Hihnalankoski model

After calibration and validation, the habitat simulations for all test discharges were done for the three test discharges for the different classes of brown trout. All repeated discharges were replaced with just one discharge. The details of the results for habitat simulations at Hihnalankoski can be found in Chapter 4.

3.10 Evaluating fish habitat quantity at Juurikoski when modified with river morphology of Hihnalankoski

The fish habitat status for Juurikoski was evaluated by theoretically moving the river structure of Hihnalankoski to Juurikoski., The essence of this was to ascertain if the fish habitat status at Juurikoski could be improved when rebuilt to have river structure similar to Hihnalankoski. The following sub-chapters explain into details the methodology for modified Juurikoski.

Juurikoski (modified)

The three test discharges into the Juurikoski theoretical 2D hydraulic model were extracted from the 1D HEC-RAS model at river cross-section 21700 m located 23.3 km below the Hamari Hydropower plant. The water levels at the start and end of the model were estimated based on the rating curves made from measured WSE at Hihnalankoski because of the assumption that Juurikoski should have the same river morphology as Hihnalankoski. Note that the calibrated and validated model for Hihnalankoski was used in this task. The minimum, mean, and maximum test discharges with a mean discharge of 5.92 m^3/s from Hamari HPP were combined to form a single hydrograph avoiding repetition of discharges. The fish habitat simulations for brown trout less than 10 cm, between 10 and 15 cm and over 15 cm were done for each of the discharges and the **WUA** in **(m^2 100 m^{-1} river reach)** computed for each discharge in the single hydrograph for modified Juurikoski. The details of the results are seen in chapter 4.

3.11 Changes in habitat location for various inflow discharges and possible stranding areas for the various brown trout classes at each study site

The changes in suitable fish habitat location at Juurikoski and Hihnalankoski were examined for combined suitability indices (CbSI) from 0.5 to 1. The CbSI for each cell position in the TIN mesh of the river reach studied were collected from the River 2D model after fish habitat simulation for discharges 2.5, 5.1, 10.4, 15.3, 20.0 and 24.5 m^3/s. The CbSI data for each cell position were exported from the River 2D fish habitat model into Arc Map 5.0 software for further post-processing into suitable results. CbSI maps were made for each of the discharges stated above. Thus in a map, each discharge CbSI area was given a single distinct colour shade. The changes in CbSI fish habitat location for each discharge were done mostly qualitatively and few times quantitatively depending on how easy it was to measure the distance between CbSI area for the different discharges in the map. This was done for brown trout classes less than 10 cm, 10 to 15 cm and over 15 cm. The details about the results of this task are shown in Chapter 4

3.12 Stranding potential at Juurikoski, Hihnalankoski and modified Juurikoski

In order to find areas of possible stranding and stranding potential within each study reach in Hihnalankoksi, Juurikoski and modified Juurikoski, the areas in the model reach covered by the maximum test discharge at 24.5 m^3/s (CbSI = 0.2 to 1) was overlapped in Arc Map with area covered by water at minimum flow at the same (CbSI = 0.2 to 1). Thus stranding potential was calculated with equation 19. At Juurikoski and modified Juurikoski minimum flow was 2.0 m^3/s whiles at Hihnalankoski minimum flow was 4.5 m^3/s.

$$Stranding\ potential = \left(\frac{A_{Q=24.5\ m^3s^{-1}} - A_{Q=minimum\ flow}}{A_{total}} \right) *\ 100\ \% \qquad (19)$$

where:

$A_{Q=24.5\ m^3s^{-1}}$ = *Area covered by water at maximum discharge of 24.3* m^3s^{-1} *at CbSI from 0.2 to 1* $\left[m^2 \right]$

$A_{Q=minimum\ flow}$ = *Area covered by water at minimum flow at CbSI from 0.2 to 1* $\left[m^2 \right]$

A_{total} = *total area of study reach* $\left[m^2 \right]$

At Juurikoski, the total area was limited to the main weir rockfills where it’s known there was no fish habitat available. The pool areas were ignored. In Hihnalankoski, the entire model reach formed the total area. The results of stranding positions and potential stranding calculated with equation 19 are shown in Chapter 4

3.13 Thermopeaking at Juurikoski, modified Juurikoski and Hihnalankoski

Thermopeaking in the lower Hamari river each was analyzed by comparing the variation in WSE and its response in the water temperature variation, and the local temperature at the same cross-section. Since the Solnist pressure loggers simultaneously measured WSE and temperature at the same measuring location, it was easy to collect thermopeaking data to analyze. Thermopeaking data for the entire lower part of Kalajoki was collected from 24th August 2019 08:00 to 26th August 2019 06:00. At cross-sections 37600, 29000, 21800, 14200, 7700 and 900, the WSE time variation was plotted with water temperature time variation analyze the level of thermopeaking along the entire river stretch. The local temperature data was acquired from Ylivieska Airport (a nearby airport in Ylivieska). Similarly, WSE and water temperature variations were collected from Juurikoski and Hihnalankoski and analyzed. The time lag between water temperature peaks in response to fluctuation in WSE was analyzed together with local temperature variations. The results of thermopeaking analysis can be found in chapter 4

4 RESULTS

4.1 Hydropeaking classification below Hamari HPP

The classification of hydropeaking in the Kalajoki based on the discharge from the Hamari hydropower plant was computed from 2006 to 2010. The average annual discharges for each year and was computed and compared to the 29 m^3/s normal average discharge from in the Kalajoki. Table 4 below shows the HP1, HP2 and impact classification of the Kalajoki based on the method of Carolli et al. (2015). It could be observed that the year 2015 had a moderate hydropeaking impact class because. The thresholds for HPI (TRHP1) and for HP2 (TRHP2) for Finland was computed by Ashraf et al. (2018) was found to be **0.29** and **1.21** respectively.

Table 4 Hydropeaking classification for Kalajoki from 2006 to 2018 based on Hamari HPP discharge according to the method of Carolli et al. (2015)

Year	HP1	HP2	TRHP1	TRHP2	Impact	Class	Annual average flow (m^3s^{-1})
2006	0.9718	1.95	0.29	1.21	3	**high**	20.345
2007	1.1658	5.86	0.29	1.21	3	**high**	21.206
2008	1.2083	9.82	0.29	1.21	3	**high**	30.396
2009	1.4273	3.68	0.29	1.21	3	**high**	12.8371
2010	1.00988	3.46	0.29	1.21	3	**high**	19.896
2011	1.134	3.8	0.29	1.21	3	**high**	20.045
2012	0.35422	2.5	0.29	1.21	3	**high**	33.962
2013	0.72494	3.58	0.29	1.21	3	**high**	22.699
2014	0.62465	2.82	0.29	1.21	3	**high**	18.718
2015	0.25233	2.1	0.29	1.21	2b	**moderate**	**36.718**
2016	0.53393	3.67	0.29	1.21	3	**high**	22.243
2017	0.81003	3.5104	0.29	1.21	3	**high**	21.101
2018	1.47873	4.2004	0.29	1.21	3	**high**	16.506

After classifying the level of hydropeaking using discharge from Hamari hydropower plant, hydropeaking classification was done using the discharge from Niskakoski gauging station located more downstream in the Kalajoki basin using the same TRHP1 and TRHP2 values for Finland. The results of this analysis are shown in Table 5.

Table 5 Hydropeaking classification (Carolli et al. (2015)) for Kalajoki from 2006 to 2018 based on discharge from Niskakoski

Year	HP1	HP2	TRHP1	TRHP2	Impact	Class	Average flow (m^3s^{-1})
2006	0.1048	0.5	0.29	1.21	1	**low**	36.21
2007	0.1773	1	0.29	1.21	1	**low**	46.27
2008	0.1984	1	0.29	1.21	1	**low**	55.26
2009	0.1424	0.45	0.29	1.21	1	**low**	27.36
2010	0.2442	1.05	0.29	1.21	1	**low**	41.52
2011	0.2207	1	0.29	1.21	1	**low**	41.29
2012	0.1743	1.2325	0.29	1.21	2b	**moderate**	62.66
2013	0.1257	0.5	0.29	1.21	1	**low**	43.87
2014	0.1264	0.4	0.29	1.21	1	**low**	35.32
2015	0.142	0.95	0.29	1.21	1	**low**	60.98
2016	0.1628	0.75	0.29	1.21	1	**low**	49.44
2017	0.1849	1	0.29	1.21	1	**low**	38.12
2018	0.1071	0.21	0.29	1.21	1	**low**	32.512

4.2 1D HEC-RAS model

In order to visualize the extent to which different hydropeaking practices from the Hamari hydropower plant affects the fluctuation in water surface elevation (WSE) downstream of the Hamari HPP during summer aiming to find the point where the fluctuation is minimal, a boxplot of daily modeled WSE and discharge variations for summer high, medium and low flow at defined cross-sections downstream of Hamari HPP towards the mouth of the Kalajoki were made. Figure 16 shows these results. Looking at figure 16, for each summer flow scenario, the left picture shows daily WSE variation whiles the right picture shows discharge variation for the test discharges. The abscissa for boxplots of WSE and daily discharge variation shows from left to right, cross-section (XS) and numbers which represent the distance in meters (m) from a point located 3.3 km upstream of the mouth of Kalajoki. Thus XS-0 is located 3.3 km from the mouth of Kalajoki.

It could be observed from both WSE boxplot graphs for different summer flow scenarios that in general, the daily WSE fluctuations are much higher at the river cross-sections near the Hamari HPP and reduces the further away the cross-sections are located from the Hamari HPP in the downstream direction. There was cross-section that showed deviations to this trend in WSE variation.

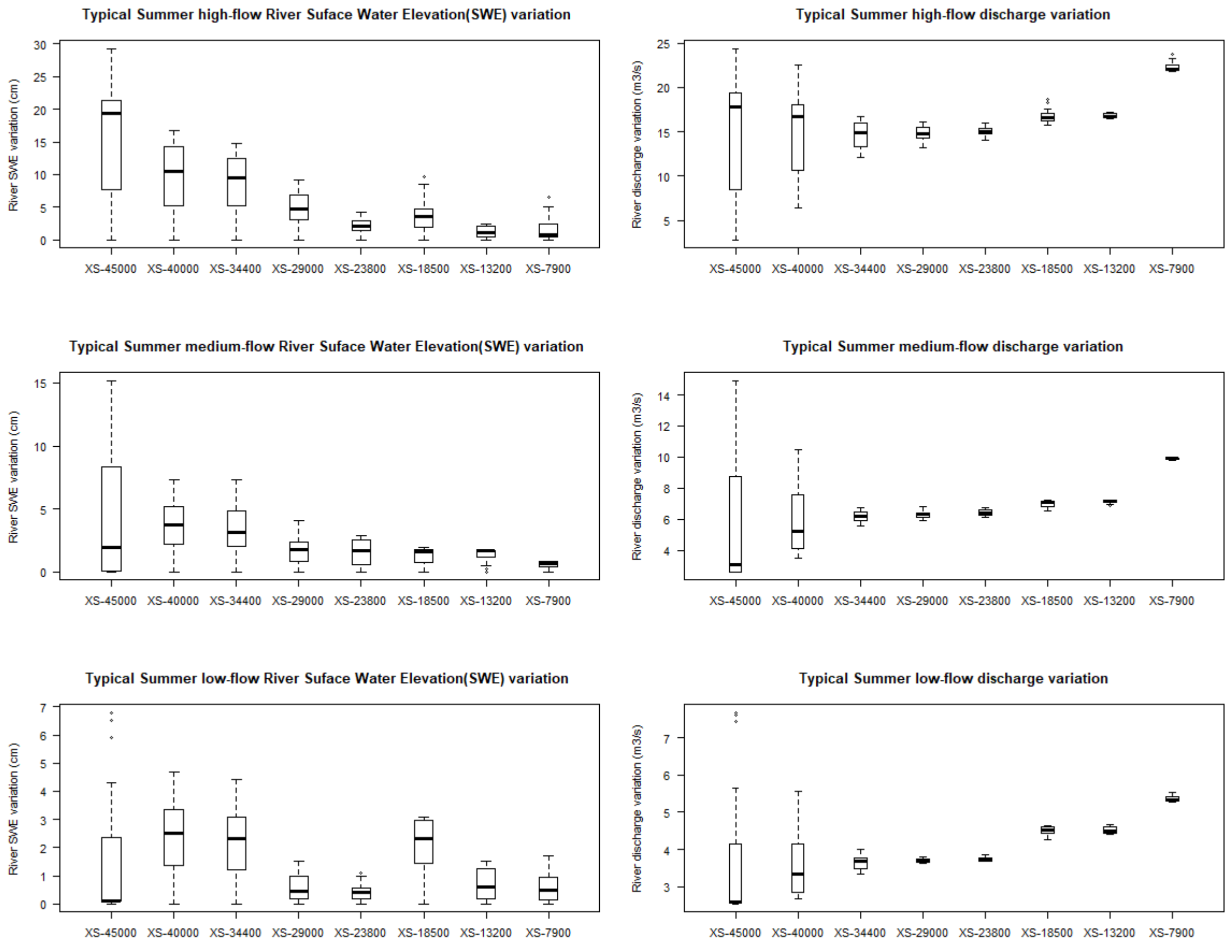


Figure 16 WSE and discharge variation at defined cross-section (XS) downstream of Hamari HPP

During summer high flow hydropeaking scenario, a daily WSE fluctuation from a maximum of 29.3 cm to 9.2 cm can be expected 16.2 km downstream of Hamari HPP.

The daily WSE fluctuation below XS-29000 m to XS-7900 m was less than 4.5 cm except at XS-18500 m and XS-7900 m which had a daily WSE fluctuation of 9.6 cm and 6.5 cm respectively. The daily discharge fluctuation was from a minimum of 3 to a maximum of 21.6 m^3/s from XS-45000 m to XS-29000 m and less than 3 m^3/s below XS-29000 m. In the summer medium flow hydropeaking scenario, a daily WSE fluctuation of 15.2 to 2.9 cm was observed from XS-45000 m to XS-23800 m and less than 2 cm below XS-23800 m to XS-7900 m. The discharge varied from 7 to 12.3 m^3/s from cross-sections XS-45000 m to XS-40000 m and less than 2 m^3/s below XS-40000 m. Summer low flow hydropeaking scenario showed a daily WSE fluctuation from a 4.4 to 6.8 cm between XS-45000 m to XS-34400 m and below 2cm from cross-sections 29000 to 7900 m with the exception of XS-18500 m which showed a fluctuation of 3.1 cm. The daily discharges fluctuated from 5.1 to 2.9 m^3/s from XS-45000 m to XS-40000 m and less than 1 m^3/s below cross-section 40000.

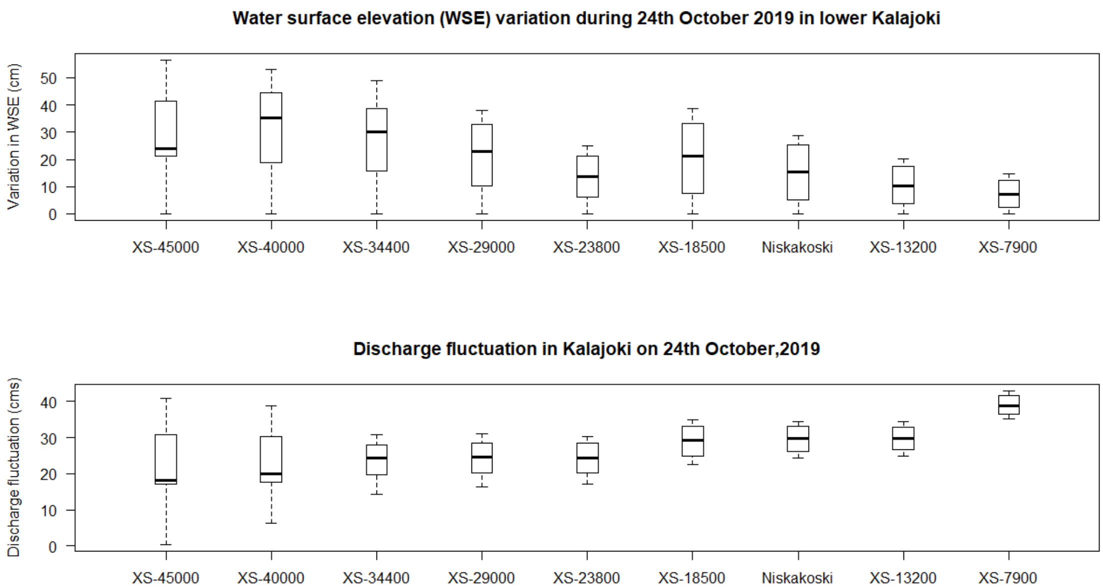


Figure 17 WSE and discharge variation at defined cross-section (XS) downstream of Hamari HPP during 24th October 2019

The results of the test of the 1D model's robustness in simulating SWE variations for much higher discharges observed in the late summer to early autumn in 2019 is shown in figure 17. With the XS-45000 to XS-40000 WSE variation was 40 to 35 cm whiles a

WSE variation of 15 cm was observed between XS-34400 to XS-18500. A WSE variation of approximately 10 to 7 cm at the lowermost cross-section from Niskakoski to XS-7900. A comparison of the modeled and observed WSE variation at Niskakoski shown in figure 18 shows that at Niskakoski, the modeled WSE variation underestimate the observed WSE variation in 1.3 cm in terms of maximum WSE fluctuation.

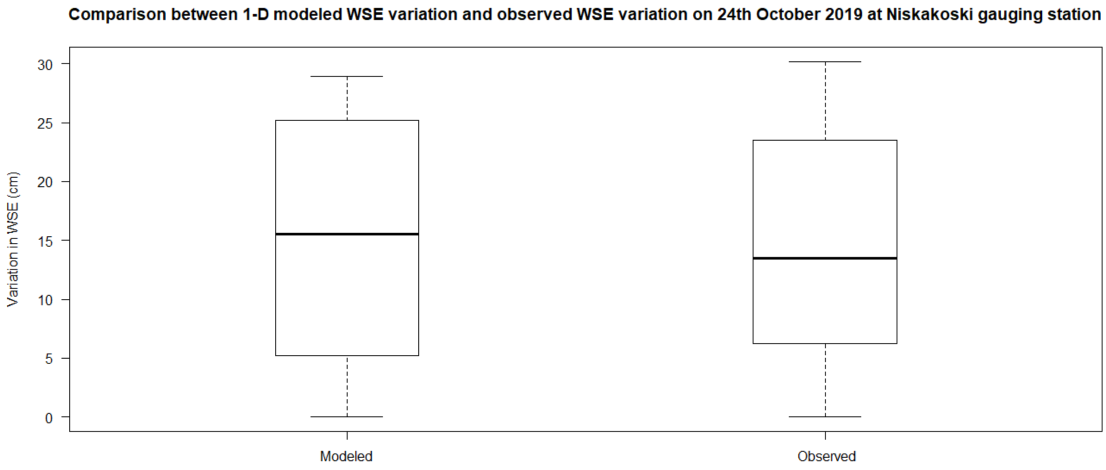


Figure 18 Comparison between modeled and observed WSE variation at Niskakoski on 24th October 2019

4.3 Two-dimensional fish habitat simulations with River 2D

Fish habitat simulation at Juurikoski

Relevant for this study is to quantitatively describe the fish habitat available in Juurikoski based on simulated discharges from the Hamari hydropower plant during a typical hydropeaking practice in the summer. In order to visualize how fish habitat available varied during typical summer hydropeaking discharge from the Hamari HPP for different classes of Brown trout in the Juurikoski, a 2D curve of discharge in m^3/s on abscissa and weighted usable area (WUA) in *m^2 per 100 m of river reach* as ordinate as shown in figure 18 were plotted. Note that the discharges on the abscissa represent the sorted discharges of all the three test discharges combined to form a single hydrograph.

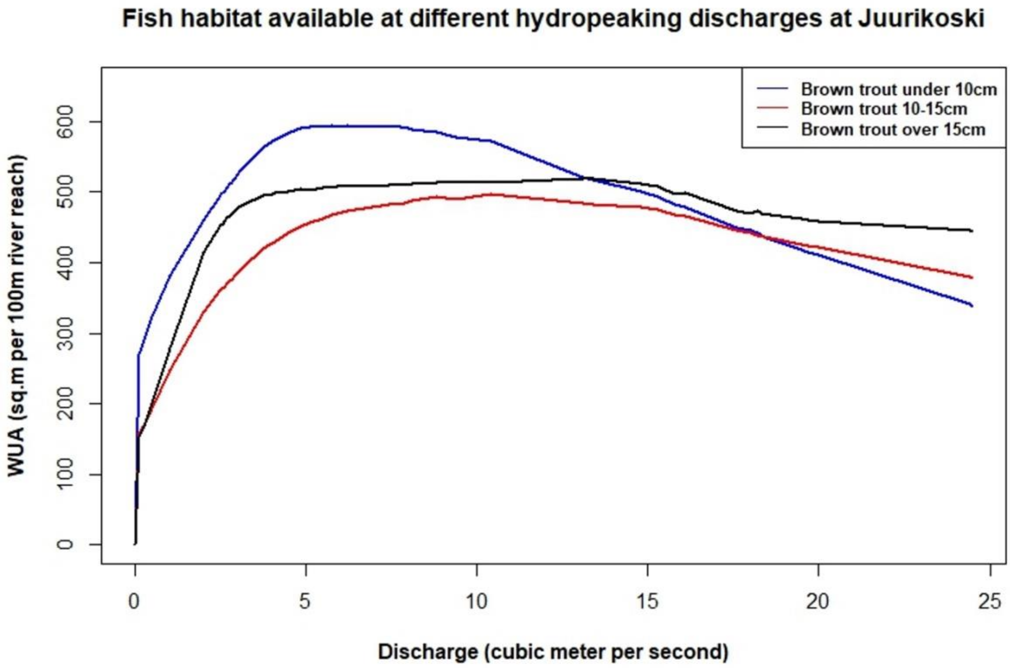


Figure 19 Fish habitat available for different classes of Brown trout in Juurikoksi during summer hydropeaking practise

Considering discharges from 2 to 12.5 m^3/s in figure 19, brown trout under 10 cm had the highest habitat quantity in terms of WUA followed by brown trout over 15 cm then brown trout from 10 to 15 cm. In all classes of brown trout, there was an initial increase in WUA as discharge increased until a point where habitat quantity decreased as discharge increase. For instance, the WUA for brown trout increased from 2.0 to 5.74 m^3/s and decreases from above 5.74 to 24.5 m^3/s. Brown trout between 10 to 15 cm, WUA increased 2.0 to 10.4 m^3/s and decreased from above 10.4 to 24.5 m^3/s. Brown trout between over 15 cm, showed increased WUA 2.0 to 13.1 m^3/s and decreased from above 13.1 to 24.5 m^3/s. The effect of various discharges on fish habitat quantity for the various class of brown trout at Juurikoski is displayed in table 6 below.

With reference to the current minimum allowable environmental flow of 2.0 m^3/s, it was important to know how much percentage of habitat quantity (WUA) had been gained above the WUA at 2.0 m^3/s as discharge increased. This results can be seen in table 12. The maximum gained WUA was 29.37% increasing the flow to 5.74 m^3/s. At the discharge of 24.5 m^3/s, 26.40% of WUA was lost. For brown trout between 10 to 15 cm, the maximum gained WUA was 50.34%. Above 10.4 m^3/s, the gained WUA (%) reduced to14.13 % at 24.5 m^3/s from Hamari HPP. Brown trout over 15 cm had a maximum gained WUA of 25.23 % at a discharge of 13.1 m^3/s and reduced above 13.1 m^3/s to 7.16 % at 24.5 m^3/s.

Figures 20, 21, and 22 show the quantity of fish habitat available in terms of WUA ($m^2 100m^{-1}$ river reach) for Brown tout under 10 cm, 10 to 15 cm and over 15 cm respectively. From those results, the suitable habitats were located around the weirs in Juurikoski as expected when product habitat computation option was used in the fish habitat simulation model. Possible stranding areas could be identified on all weirs 1, 2, 3 and 4 when for example the simulation results for 24.5 m^3/s is compared with the current allowable minimum environmental flow of 2.0 m^3/s. A more detailed description of stranding results on all study sites would be displayed in later chapters.

At lower discharges from the Hamari HPP from 2.5 to 4 m^3/s the suitable habitat for brown trout under 10 cm were situated closer to the weir opening where most of the river water passed and left the outer parts close to the river bank almost dry without any habitat at all. As the discharge began to increase from 10 m^3/s and beyond, the middle part close to the weir opening begun to lose their suitable habitat moving outwards spreading out around the rockfills around the weirs and towards the river bank which was initially dry when the discharges were 4 m^3/s and below. As the discharge increased above 15.3 m^3/s, the weirs 1A, 3A, 4A, and 4B begun to loose their suitable habitats whiles suitable habitat on 2C, 2B, 1B and 3B were maintained.

Brown trout class between 10 to 15 cm showed suitable habitat positioned within the fast water moving sections within the weir opening for lower discharge from 4.0 m^3/s and below. Similarly, during high discharges from 10.4 m^3/s and beyond, the suitable habitat located near and around weirs 1A, 3A, 4B and 4A begun to lose gradually their suitable habitat moving it away from the weir opening to towards the river bank or nearby island. Brown trout class above 15 cm, had a stable habitat as discharges increased from 10.4 to 24.5 m^3/s with most suitable habitats located in front of and behind the rock fills around the weirs near to the pools or in the pools.

Table 6 Effect of various discharges on fish habitat available in WUA (m^2 $100m^{-1}$ river reach) at Juurikoski

Q_Hamari HPP (m^3/s)	Brown Trout under 10cm			
	WUA(m^2)	Total(m^2)	WUA (m^2/100m River Reach)	Gained WUA (%)
2	2454.12	46392.91	459.57	0.00
2.5	2643.41	46392.81	495.02	7.71
3	2796.16	46392.91	523.63	13.94
4	3057.66	46393.03	572.60	24.59
5.5	3159.37	46392.41	591.64	28.74
5.747	3174.87	46392.68	594.54	29.37
6.2	3171.44	46392.56	593.90	29.23
7.748	3160.32	46392.46	591.82	28.78
10.4	3051.37	46392.46	571.42	24.34
15.3	2631.87	46392.96	492.86	7.24
24.5	1806.27	46392.54	338.25	-26.40
Q_Hamari HPP (m^3/s)	Brown Trout 10-15cm			
	WUA(m^2)	Total(m^2)	WUA (m^2/100m River Reach)	Gained WUA (%)
2	1764.87	46392.91	330.50	0.00
2.5	1928.91	46392.81	361.22	9.29
3	2057.03	46392.91	385.21	16.55
4	2280.91	46393.03	427.14	29.24
5.1	2437.31	46392.74	456.43	38.10
8	2597.99	46392.72	486.51	47.21
10.4	2653.23	46392.46	496.86	50.34
13.4	2579.77	46392.42	483.10	46.17
14.8	2554.35	46392.37	478.34	44.73
15.3	2535.44	46392.96	474.80	43.66
24.5	2014.30	46392.54	377.21	14.13
Q_Hamari HPP (m^3/s)	Brown Trout over 15cm			
	WUA(m^2)	Total(m^2)	WUA (m^2/100m River Reach)	Gained WUA (%)
2	2214.01	46392.91	414.61	0.00
2.5	2418.44	46392.81	452.89	9.23
3	2544.08	46392.91	476.42	14.91
4	2655.95	46393.03	497.37	19.96
6.2	2715.83	46392.56	508.58	22.67
8	2725.26	46392.72	510.35	23.09
10.4	2745.62	46392.45	514.16	24.01
13.1	2772.50	46392.96	519.20	25.23
14.8	2729.54	46392.37	511.15	23.29
15.3	2714.63	46392.96	508.36	22.61
24.5	2372.42	46392.54	444.27	7.16

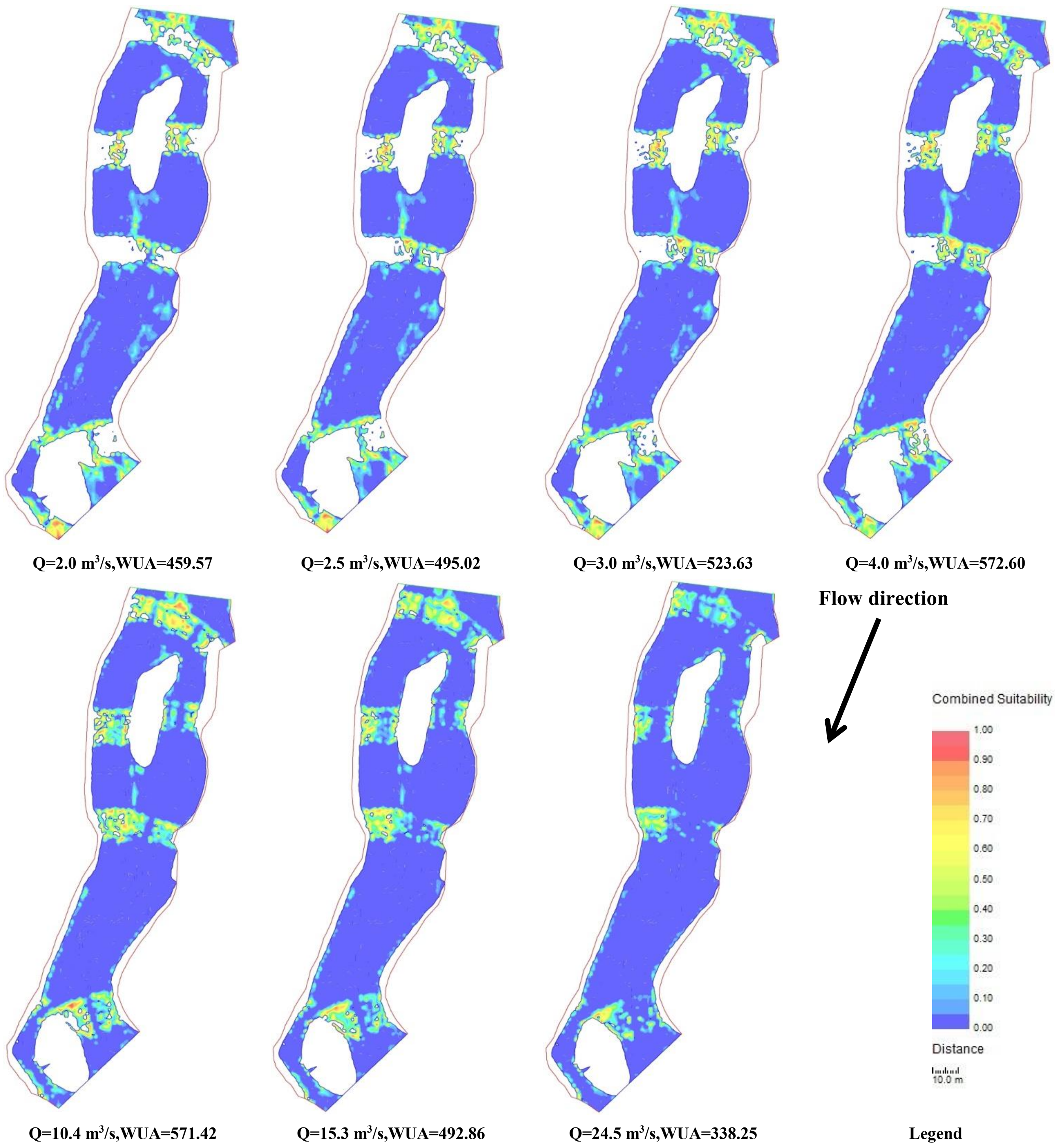


Figure 20 WUA (m^2100m^{-1} river reach) for some different test discharges for brown trout under 10cm at Juurikoski.

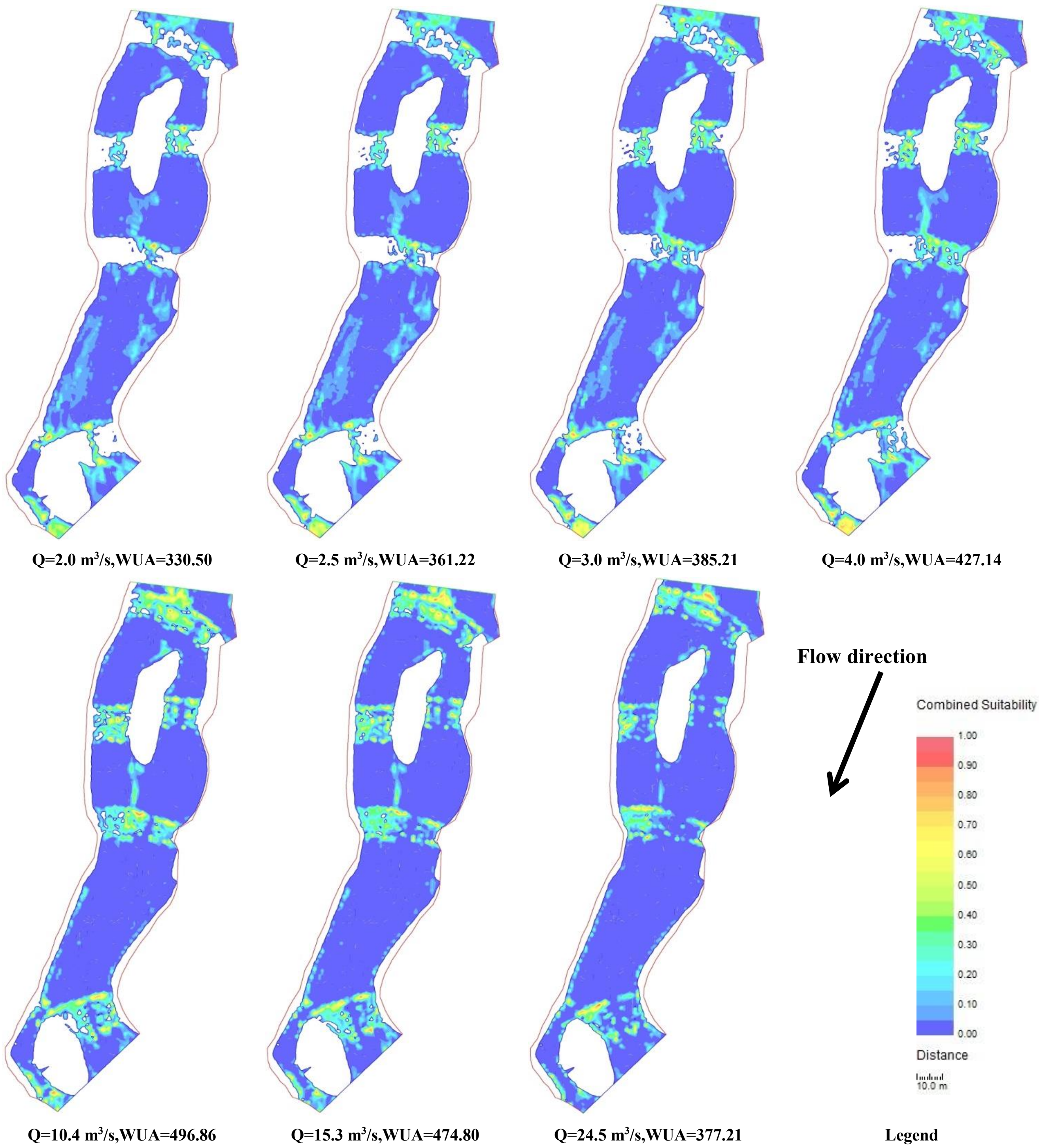


Figure 21 WUA ($m^2 100m^{-1}$river reach) for some different test discharges for brown trout between 10 to 15cm at Juurikoski.

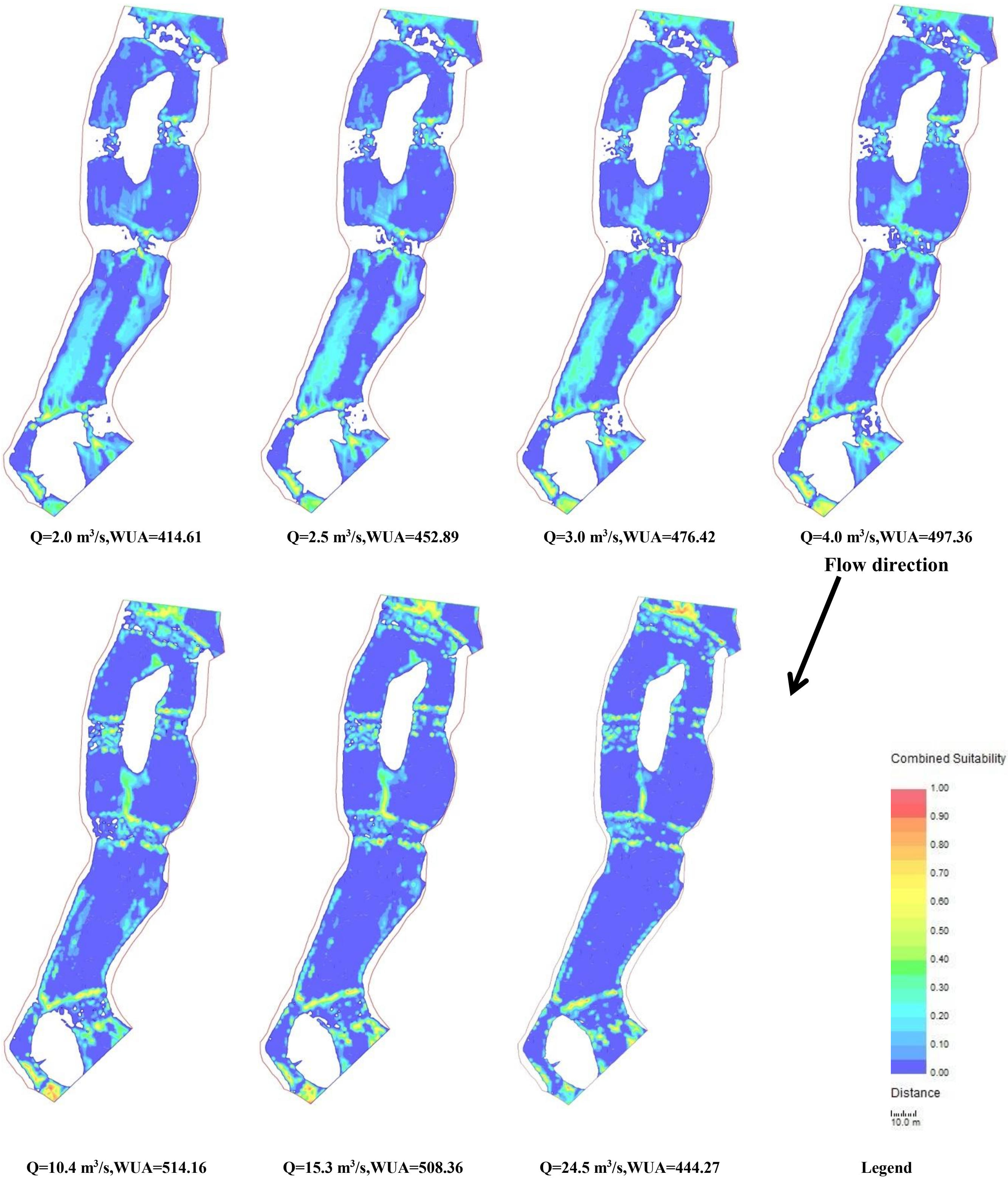


Figure 22 WUA ($m^2 100m^{-1}$RR) for some different test discharges for brown trout over 15cm at Juurikoski

Fish habitat simulation based on the theoretical movement of Hihnalankoski to Juurikoski

To ascertain how the quantity of fish habitat available at Juurikoski would be improved when it assumes the river structure of Hihnalankoski, the habitat available in terms of WUA (m^2 per 100m river reach) for the three classes of brown trout were plotted together in figure 21 shown below. From the results, brown under 10 cm had an average habitat quantity of 1400.30 (m^2 per 100m RR) and a maximum of 2032.11 (m^2 per 100m RR) at a discharge of 2.59 m^3/s. The highest fish quantities were 1900.16 to 2032.11 (m^2 per 100m RR) and produced between discharge from 2.0 to 4.48 m^3/s. The fish quantity began to reduce as discharge increased from 4.48 to 24.5 m^3/s. The least fish habitat quantity of 501.96 (m^2 per 100m RR) was produced at a discharge of 24.5 m^3/s.

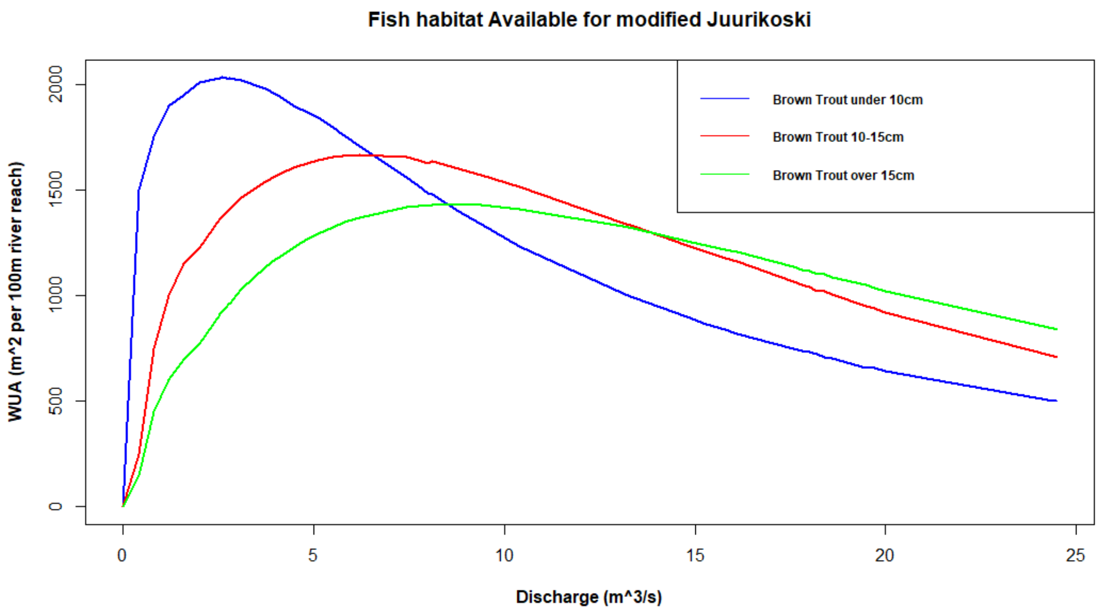


Figure 23 Fish habitat available at Juurikoski (modified with Hihnalankoski river structure) for different classes of Brown trout

Brown trout between 10 to 15 cm had an average fish habitat of 1269.45 (m^2 per 100m RR) and a maximum of 1664.23 (m^2 $100m^{-1}$ river reach) produced at a discharge of 6.20 m^3/s. The curve shows that the highest fish habitat quantities from 1513.31 to 1664.23 (m^2 $100m^{-1}$ river reach) were produced during discharges from 3.74 to 10.40 m^3/s.

Brown trout over 15 cm had an average fish habitat of 177.96 (m^2 $100m^{-1}$ river reach) and a maximum of 1431.40 (m^2 $100m^{-1}$ river reach) produced at a discharge of 8.10 m^3/s. The highest fish habitat quantities of 1317.74 to 1431.40 (m^2 $100m^{-1}$ river reach) were produced when discharge from Hamari HPP was from 5.5 to 13.4 m^3/s.

To clearly see how fish habitat improves when the current river structure of Juurikoski is compared to a new Juurikoski with a river structure of Hihnalankoski, the fish habitat quantities were compared for all classes of brown trout in figure 24 below. The results from the comparison showed an increased average fish habitat of 267.25 %, 310.66% and 237.49 % on all discharges for brown trout under 10 cm , 10 to 15 cm and over 15 cm respectively when Juurikoski structure is modified to assume river structure of Hihnalankoski. The results show an improved fish habitat from 200 to 437.23% from 2.0 to 5.5 m^3/s from brown trout under 10 cm. brown trout between 10 to 15 cm showed an improved fish habitat from 304 to 370.7% for discharge from 2.0 to 10.40 m^3/s. Brown trout over 15cm showed an improved habitat from 200 to 280.1% for discharges from 2.54 to 20.0 m^3/s. In general, the fish habitat available improved for all classes of brown trout when Juurikoski assumed the river structure of Hihnalankoski especially in the lower discharges from the current minimum flow of 2.0 m^3/s to about 14.0 m^3/s.

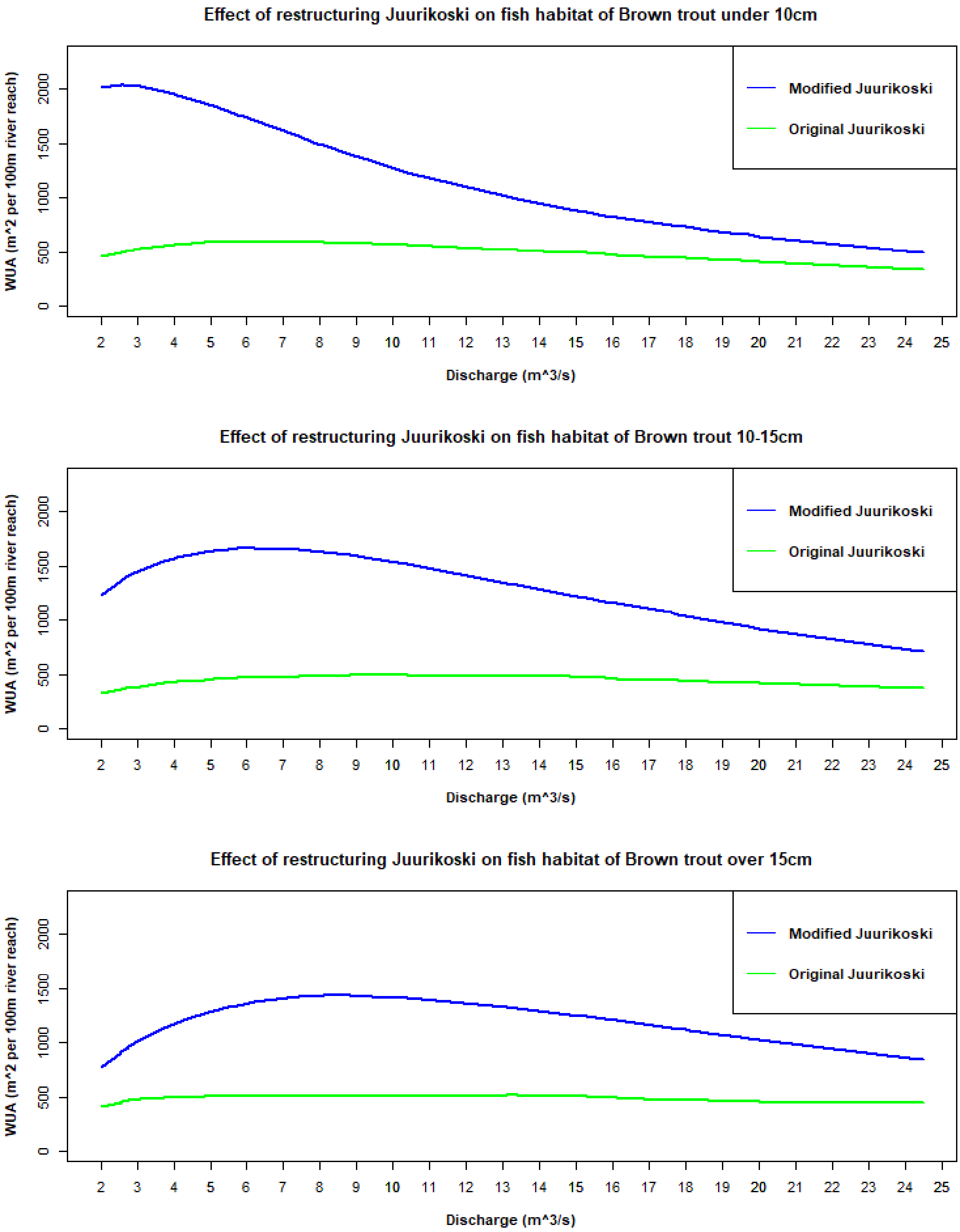


Figure 24 Effect of Hihnalankoski river structure at Juurikoski

Fish habitat simulation at Hihnalankoski

The fish habitat available at Hihnalankoski for the modeled discharges from 4.43 to 17.34 m^3/s were plotted together in figure 23 to visualize the variation in fish habitat quantity for various brown trout classes. The result showed for brown trout under 10 cm an initial fish habitat quantity of 1907. (m^2 $100m^{-1}$ river reach) at a discharge of 4.43 m^3/s declined fairly steadily to 762.43 (m^2 $100m^{-1}$ river reach) at a discharge of 17.34 m^3/s. Brown trout under 10 cm had an average fish habitat of 1362.9 (m^2 $100m^{-1}$ river reach) with maximum and minimum fish habitat quantity of 1907.38 and 762.43 (m^2 per 100m RR) at an inflow discharge of 4.43 and 17.34 m^3/s respectively. Note that the discharges at Hihnalankoski didn't fall below 4.43 m^3/s. If 2.0 to 24.5 m^3/s is considered then the curves in figure 23 will replace figure 25. Thus figure 25 shows just some portions of figure 25 with different discharges between the range hence the different looks.

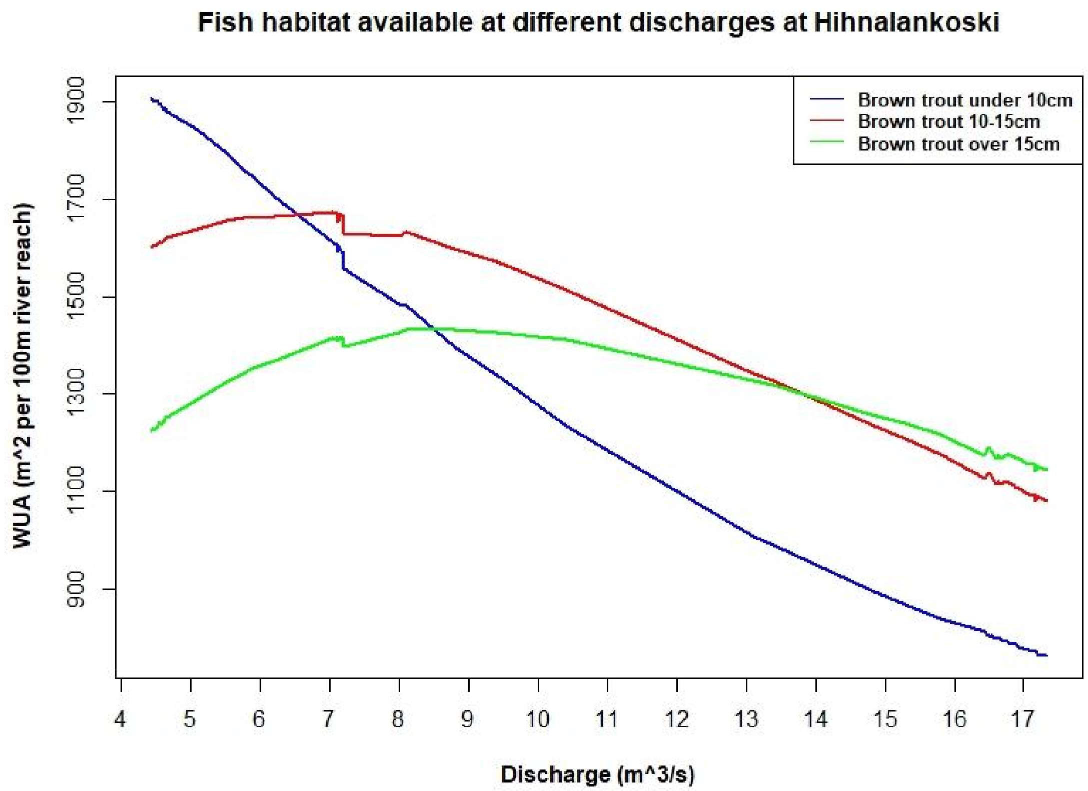


Figure 25 Fish habitat available at Hihnalankoski during summer hydropeaking events from Hamari HPP

Brown trout between 10 to 15 cm had an average fish habitat quantity of 1418.62 (m^2 $100m^{-1}$ river reach) and a maximum and minimum fish habitat quantity of 1674.33 and 1078.21 (m^2 $100m^{-1}$ river reach) at an inflow discharge of 7.09 and 17.18m^3/s respectively. Similarly to brown trout between 10 to 15 cm, brown trout over 15 cm had an average fish habitat quantity of 125293 (m^2 $100m^{-1}$ river reach) with a maximum and minimum fish habitat quantity of 1415.35 and 1140.14 (m^2 $100m^{-1}$ river reach) respectively. Combining the results from figure 26, 27 and 28, it could be observed from that the suitability map in Hihnalankoski in figure 24 for brown trout under 10cm that fish habitat quantity available is much abundant in lower discharges from 4.43 to 7.16 m^3/s above. Increased discharges from 7.16 to 17.34 m^3/s showed declined suitable fish habitat fairly throughout the study reach. Brown trout between 10 to 15 cm and over 15 cm showed fairly similar results.

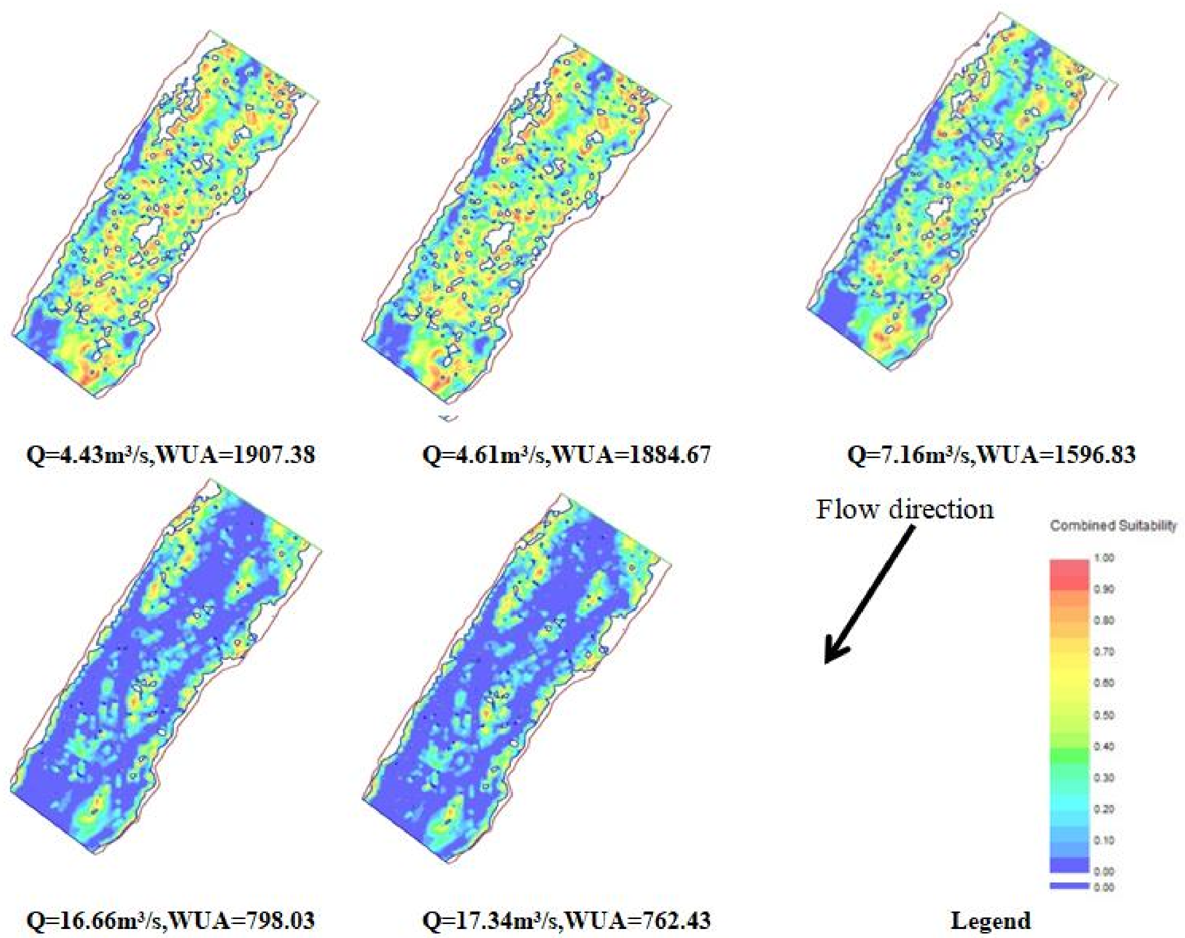


Figure 26 Fish habitat simulation results for brown trout under 10 cm at Hihnalankoski

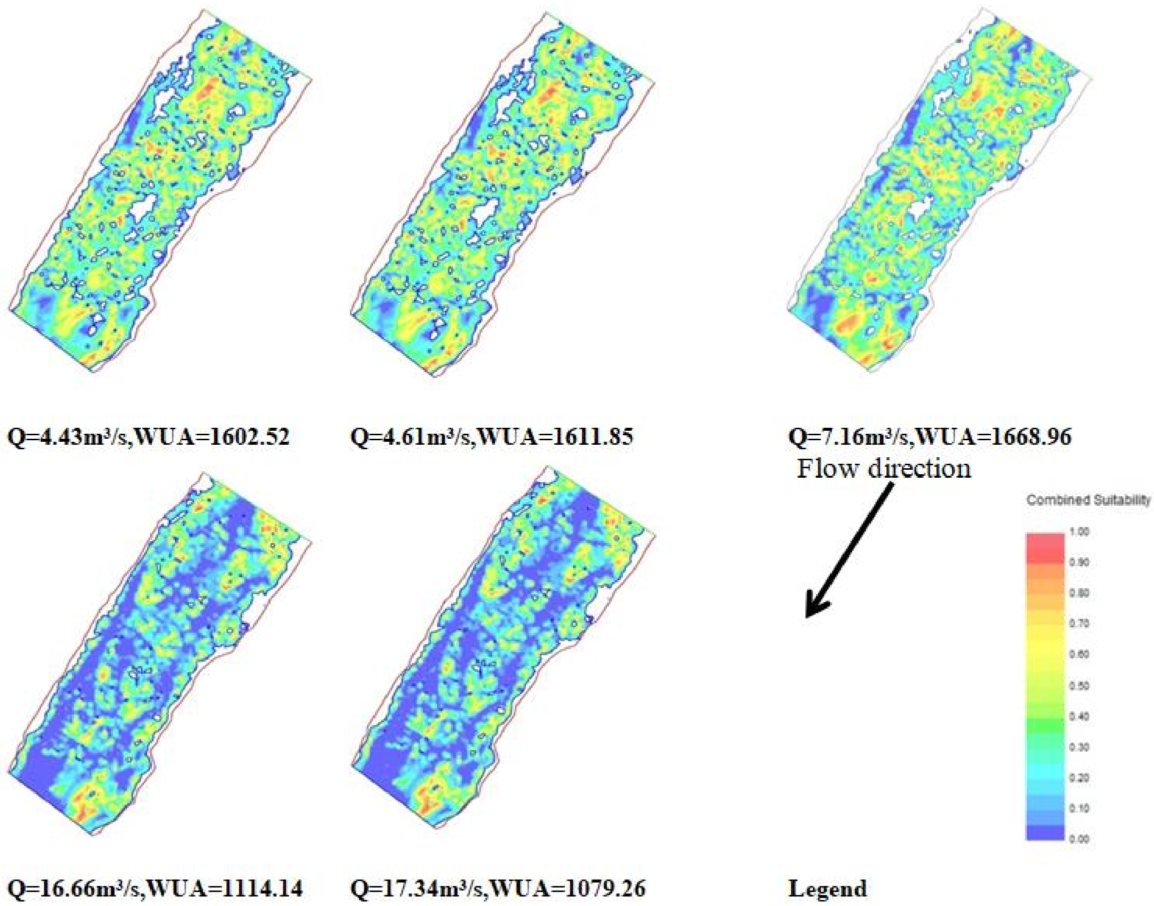


Figure 27 Fish habitat simulation results for brown trout 10-15 cm at Hihnalankoski

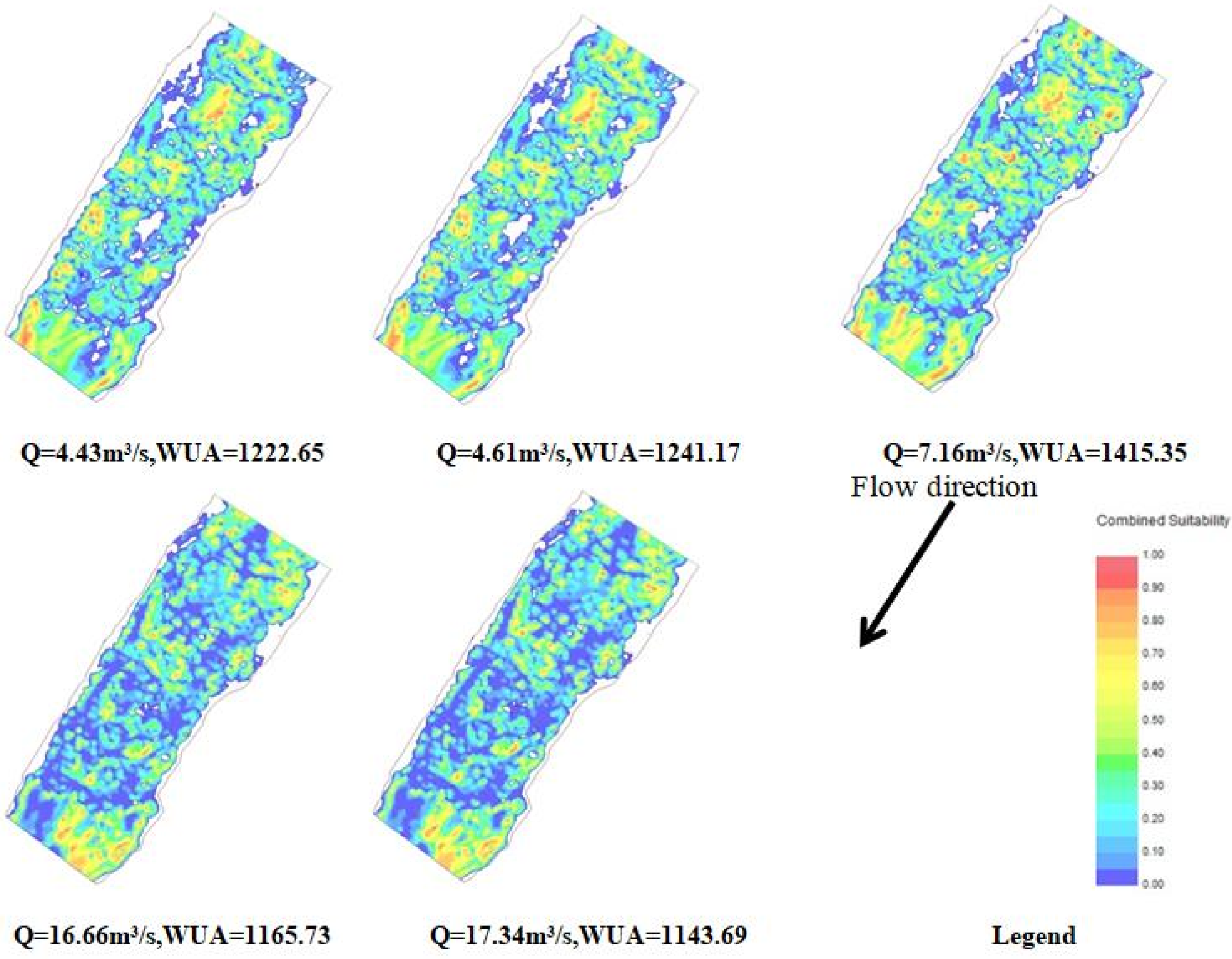


Figure 28 Fish habitat simulation results for brown trout over 15 cm at Hihnalankoski

4.4 Movement in habitat location in varying inflow discharges

It was one of the tasks of this study to measure how much the suitable fish habitat for the different classes of Brown trout changes in location as discharges fluctuate due to hydropeaking at Juurikoski and Hihnalankoski. To visualize and measure these changes in habitat location, a well suitable habitat with CbSI from 0.5 to 1 for discharges 2.5, 5.1, 10.4, 20.0, and 24.5 m^3/s were imported into ArcMap from the fish habitat simulation results from River 2D. Figures 28, 29 and 30 show the positions of suitable brown trout for those under 10 cm, 10 to 15 cm and over 15 cm respectively.

Change in suitable fish habitat location at Juurikosi

Brown tout under 10 cm

As seen in figure 29, Brown trout under 10 cm, the suitable fish habitat were located just around the weirs either slightly in the upstream near the pools of right on top of the rock fill around the weirs. There were no suitable habitats observed for discharge 24.5 m^3/s within the defined CbSI limits which was from 0.5 to 1. On the hand, countable distinct tiny or large ‘colonies’ of suitable brown trout habitats were observed for discharges 2.5, 5.1, 10.4, and 20.0 m^3/s. At the discharge of 20.0 m^3/s, eight distinct habitats were formed around weir 3B. Four were of these habitats were larger than 1 m^2 while the other four were less than 1 m^2. The largest colonies were 24.95, 18.69, 2.38 and 4.09 m^2. Those larger colonies of brown trout were situated from 12.5 to 16.7 m apart. Aside these habitats around weir 3B, three distinct suitable habitat region were created around weir 1B one of which was less than 1 m^2 and the other two greater than 1 m^2 specifically 4.18 and 1.41 m^2. Those two habitats around weir 1B were 8.3 m apart. The distance between the habitat colony around weir 3B and 1B was 91.7 m. When the discharge reduced to 15.3 m^3/s, four distinct habitat colony was formed around weir 3B whiles 7 were formed around weir 1B. Out of the 4 habitats around weir 3B, one was less than 1 m^2 whiles three were above 1 m^2 specifically with areas 10.98, 5.42 and 32.95 m^2. Three out of the 7 habitats formed around weir 1B were more than 1 m^2.

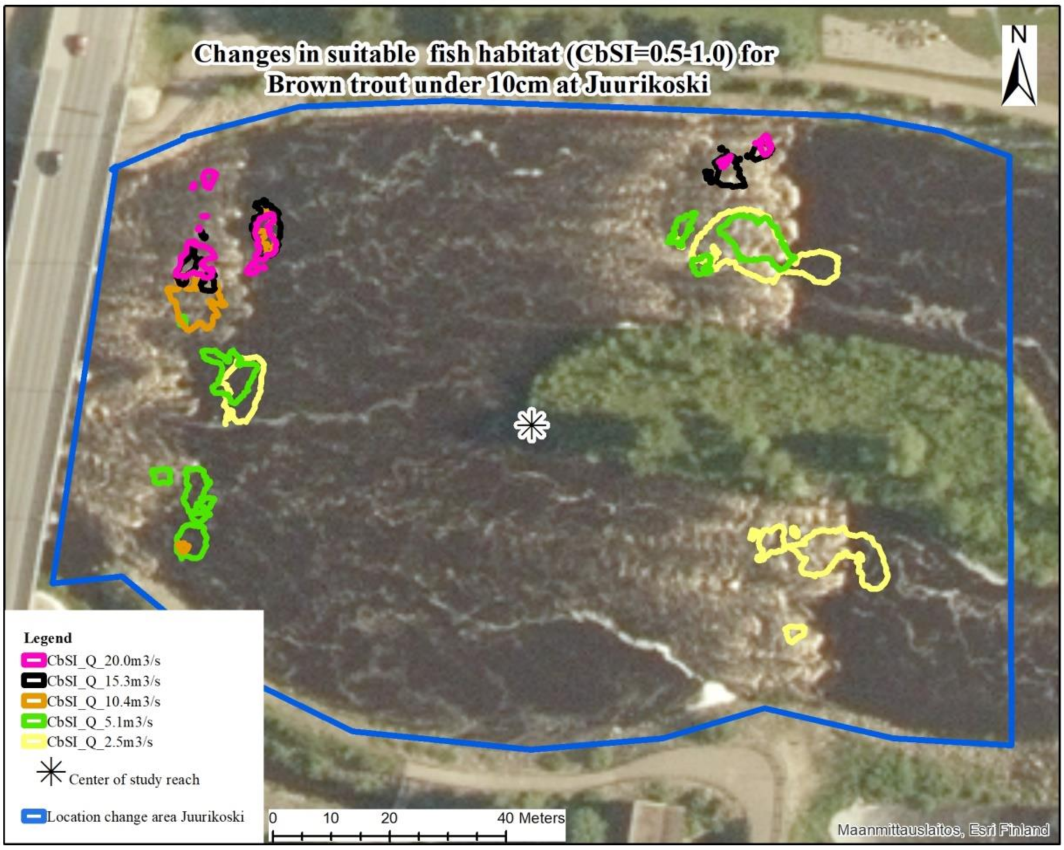


Figure 29 Fish habitat location change in Juurikoski for Brown trout under 10 cm

The suitable habitats around weir 3B were on the average 10 m apart whiles those on around weir 1B were about 2.5 m apart. The habitat colonies formed around weir 3B and 1B were 62.5 m apart. As discharge further reduces to 10.4 m^3/s, one suitable habitat (1.91 m^2) was created around weir 3A and two (13.78 and 1.26 m^2) around weir 3B. The distance between habitat colonies between 3A and 3B was 42.35 m. At 5.1 m^3/s, 2 suitable habitats (1.26 and 41.44 m^2) were created around weir 3A, three large habitats (23.47, 6.34, 27.31 m^2) around weir 3A and again three large suitable habitats (65.76,7.24 and 11.16 m^2) around weir 1B. The distance between habitat colonies between weirs 3B and 3A was 35.3 m whiles that between habitat at 1B to 3A or to 3B was 94.12 to 105.88 m. At 2.5 m^3/s, one large suitable habitat above 1 m^2 (54.26 m^2) was created around weir 3B, five large habitats (89.37, 6.13, 17.2, 1.09, and 1.22, m^2) around weir 1A and again one large suitable habitat (164.18 m^2) around weir 1B. The average distance from habitats located on weir 3B to 1B and 3B to 1A was 94.12 and

111.76 m. The distance from habitat located on weir 1B to 1A was approximately 129 m around the island. The distance between suitable habitats created within weir 1B, 3 and 1A as discharge fluctuates from 2.5 m^3/s to 15.3 m^3/s to 5.1 m^3/s to 2.5 m^3/s or vice versa was on the average was less than 5m, 15m and 11.76 m respectively.

Brown trout 10-15 cm

The habitat location change during hydropeaking at Juurikoski within the selected study area and CbSI limits of 0.5 to 1 as shown in figure 30 showed distinct habitat colonies only for discharges 20, 10.4 and 5.1 m^3/s. At 20 m^3/s, one small suitable habitat area (0.7 m^2) only was formed around weir 1B. At 10.4 m^3/s one large suitable habitat areas (9.69 m^2) only was formed around weir 3B. At 5.1 m^3/s, one suitable habitat (8.35 m^2) was formed around weir 1A whiles two suitable habitat areas (10.94 and 0.15 m^2) were formed around weir 1B. The distance between suitable habitats created on weir 1B for discharge change for 5.1 to 20 m^3/s was 17. 64m. On weir 3B there only one colony of suitable habitat. The distance between suitable habitat colony from weir 3B to 1A and 3B to 1B was 117.65 m and 94.12 m respectively. The distance between suitable habitat colonies on weir 1B to 1A was 158.82 m around the island within the study area.

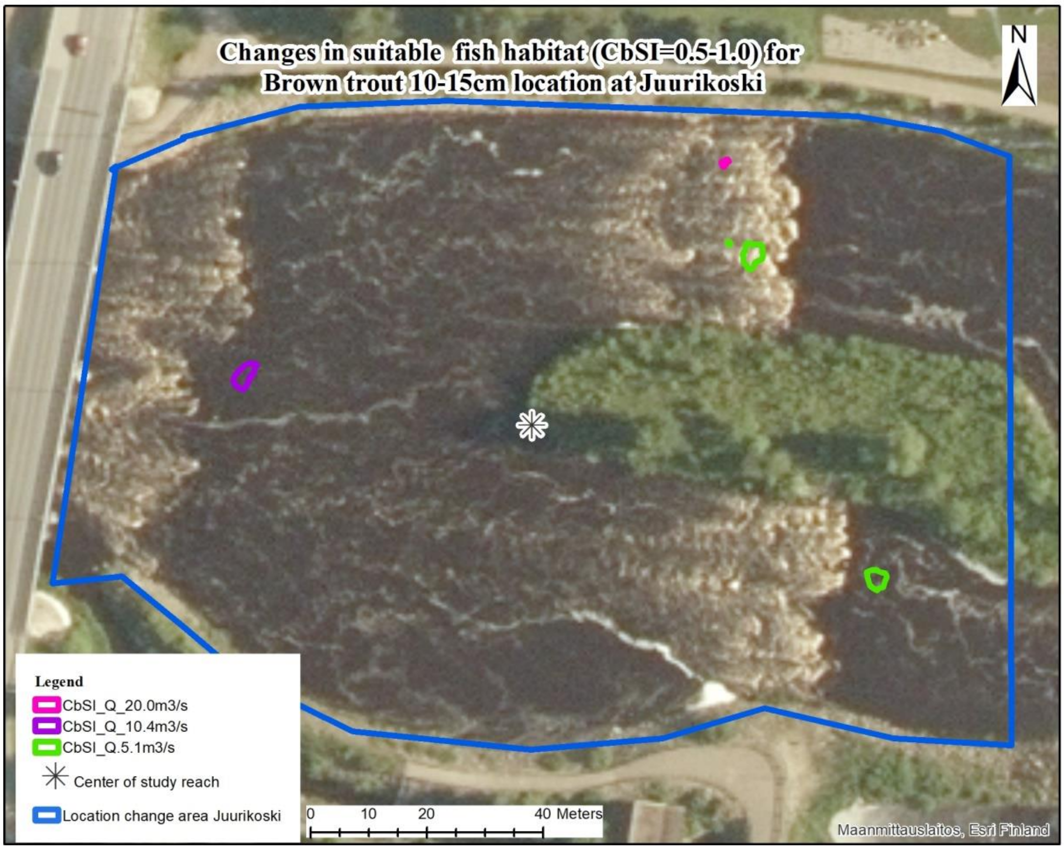


Figure 30 Fish habitat location change in Juurikoski for Brown trout under 10 to 15 cm

Brown trout over 15 cm

Location change of suitable Brown trout habitat with CbSI from 0.5 to 1.0 was measured for Brown trout over 15cm from figure 31. In this analysis, measurable distinct colonies of with the set CbSI limits were observed for discharges 20, 15.3, and 10.4 m^3/s. At 20 m^3/s discharge from the Hamari HPP, a total of 4 distinct habitat regions were seen. One colony with an area of 13.32 m^2 was could be visualized around the rock fill of weir 3B whiles the other three colonies with areas 4.03, 3.98 and 3.66 m^2 were located with the pool between island and weir 3. At discharges of 15.3 and 10.4 m^3/s, one habitat each could be seen within the same pool area within weir 3B and island. The distance between the suitable habitat created on top of rockfill of weir 3B to the suitable habitats in the pools was 29.4 m. Within the pool, it could be seen that the two small colonies formed at a discharge of 20 m^3/s are isolated from those formed at discharges 15.3 and 10.4 m^3/s. The isolated habitats were located 17.65 m from those other habitats in the pools.

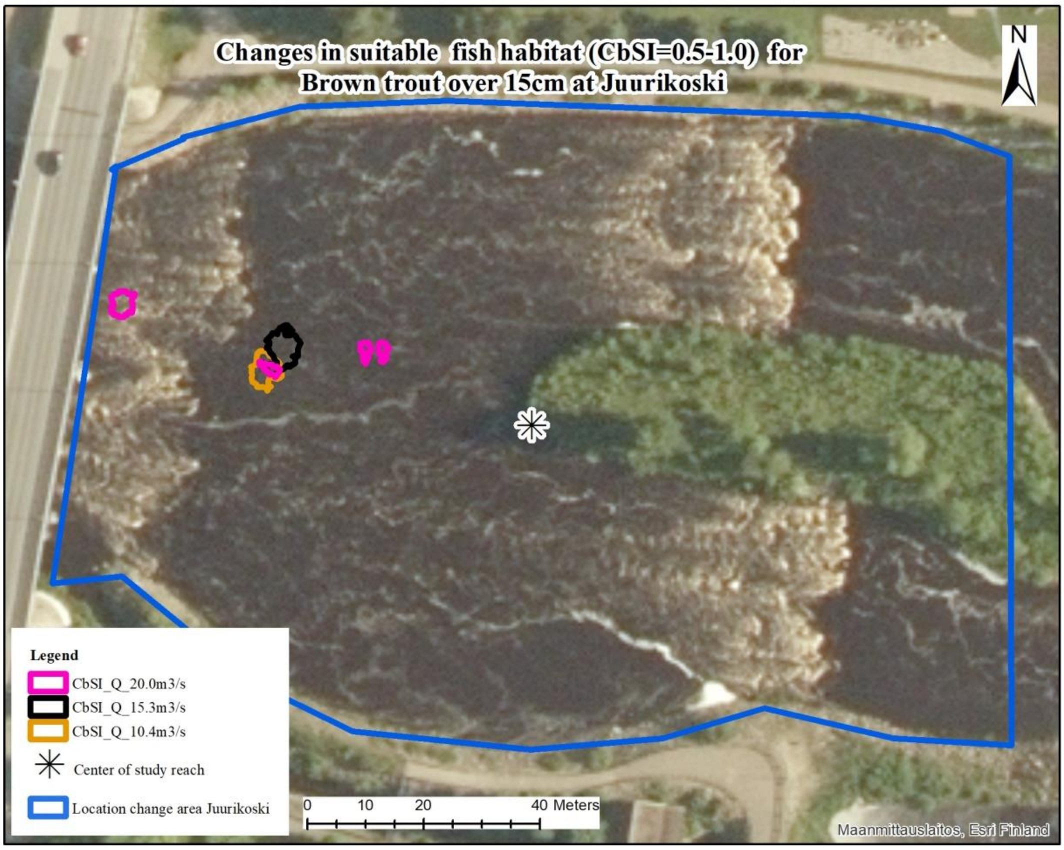


Figure 31 Fish habitat location change in Juurikoski for Brown trout over 15 cm

Changes in suitable fish habitat location at Modified Juurikoski with river structure of Hihnalankoski

To ascertain how much fish habitat location moves at various discharges during hydropeaking when river structure of Juurikoski is modified into river structure of Hihnalankoski, the CbSI from 0.5 to 1 was exported from the fish habitat simulation results into Arc map to produce suitability maps for different discharges with one colour code for the CbSI from 0.5 to 1. This was done for brown trout under 10 cm, 10-15 cm and over 15cm and the view of the results shown figures 32, 33, 34 respectively.

Brown trout under 10 cm

In the brown trout under 10 cm scenario shown in, the results for an inflow of 2.45 m^3/s showed continuous and uniformly distributed habitats that covered very much entire study area. The maximum distance between suitable habitat was less than 4m. At 5.10 m^3/s there was a lot of suitable areas uniformly distributed within the study reach similar to that for 2.5 m^3/s but this time the colonies were much spaced apart. The maximum distance between the most spaced suitable habitats was 13.85m whiles the minimum distance was about 3.5 m. As the discharge increased to 10.4 m^3/s, the suitable habitat had significantly reduced and very much spaced out fairly uniformly within the study reach. The maximum distance between the two most spaced out habitats was 34.62 m and the minimum was 11.54 m. At 15.3 m^3/s, the suitable habitats were about 10 colonies positioned near the banks of the study reach with a maximum and minimum spacing of 103.8 m and 23.1 m respectively. At 20 to 24.5 m^3/s, there were just 3 to 4 large colonies near the upstream right bank. In general, it was evident that lower flows from 2.54 to 5.1 m^3/s produced more suitable habitats that were less spaced apart for brown trout under 10 whiles the higher flows for above 5.1 diminished the amount of suitable habitat spacing them further apart.

Brown trout under 10-15 cm

The suitable habitats for Brown trout class from 10 to 15 cm are shown in figure 32 below. At an inflow of 2.54 m^3/s, there were few large suitable areas mixed with few small suitable areas all fairly located within the middle part of the river reach. The most spaced out suitable colonies was 46 m and the least spaced out colonies were less than 2 m apart. An inflow of 5.1 m^3/s produced much larger suitable colonies with a maximum and minimum spacing of 23.1 m and 4.6 m respectively. At an inflow of 10.4 m^3/s, the suitable areas although few compared to that of 5.1 m^3/s they were more spaced out with a maximum spacing of 34.62 m. Inflows 15.3, 20 and 24.5 m^3/s produced fewer suitable regions which were spaced out at a maximum of 57.7 to 103.8 m. Inflow 24.5 m^3/s show much smaller suitable areas.

Brown trout 10-15 cm

Brown trout over 15 cm suitable habitat are shown in figure 33. An inflow of 2.54 m^3/s, there were 9 colonies of fish habitat uniformly spread throughout the study reach. The maximum and minimum spacing between suitable habitats were 30 and 23.1 m respectively. The suitable habitats for 5.1 m^3/s were 18 with a maximum and minimum spacing of 23.1 and 4.6 m respectively. The number of suitable habitats at 10.4 m^3/s was much similar to that of 5.1 m^3/s but with a maximum and minimum spacing of 34.6 and 6.9 m respectively. The suitable habitat at an inflow of 15.3 m^3/s showed fewer large suitable habitats than small suitable habitats with a maximum spacing of 43.85 m with the largest suitable habitat located in the pools in the left down-most stream part of the study reach. Inflows of 20 to 24.5 m^3/s showed much few suitable habitats which were very much spaced out at a maximum of 96.9 m and a minimum of 9.23 m.

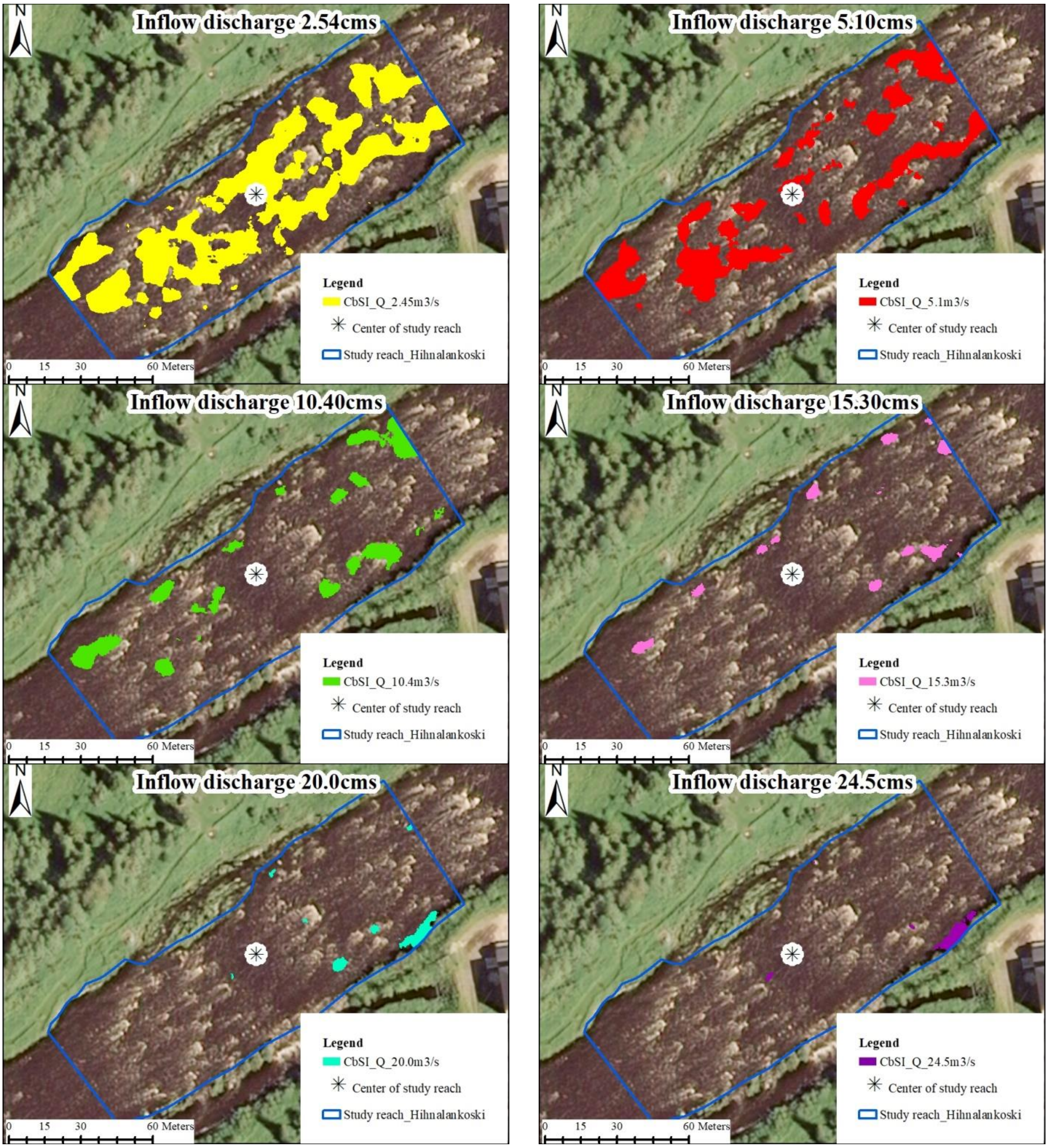


Figure 32 Changes in fish habitat location at various discharges at modified Juurikoski for Brown trout under 10 cm

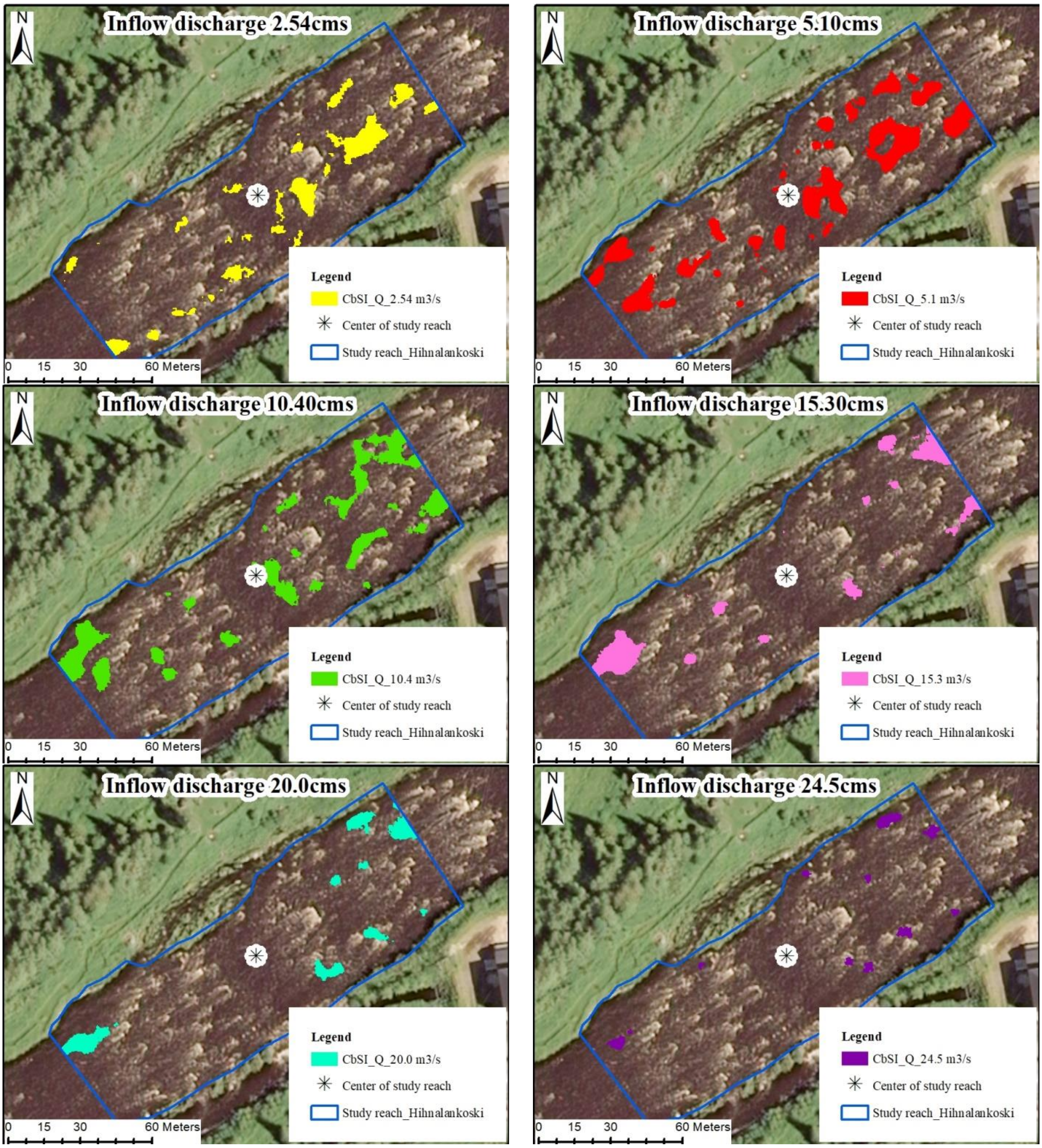


Figure 33 Changes in fish habitat location at various discharges at modified Juurikoski for brown trout 10-15 cm

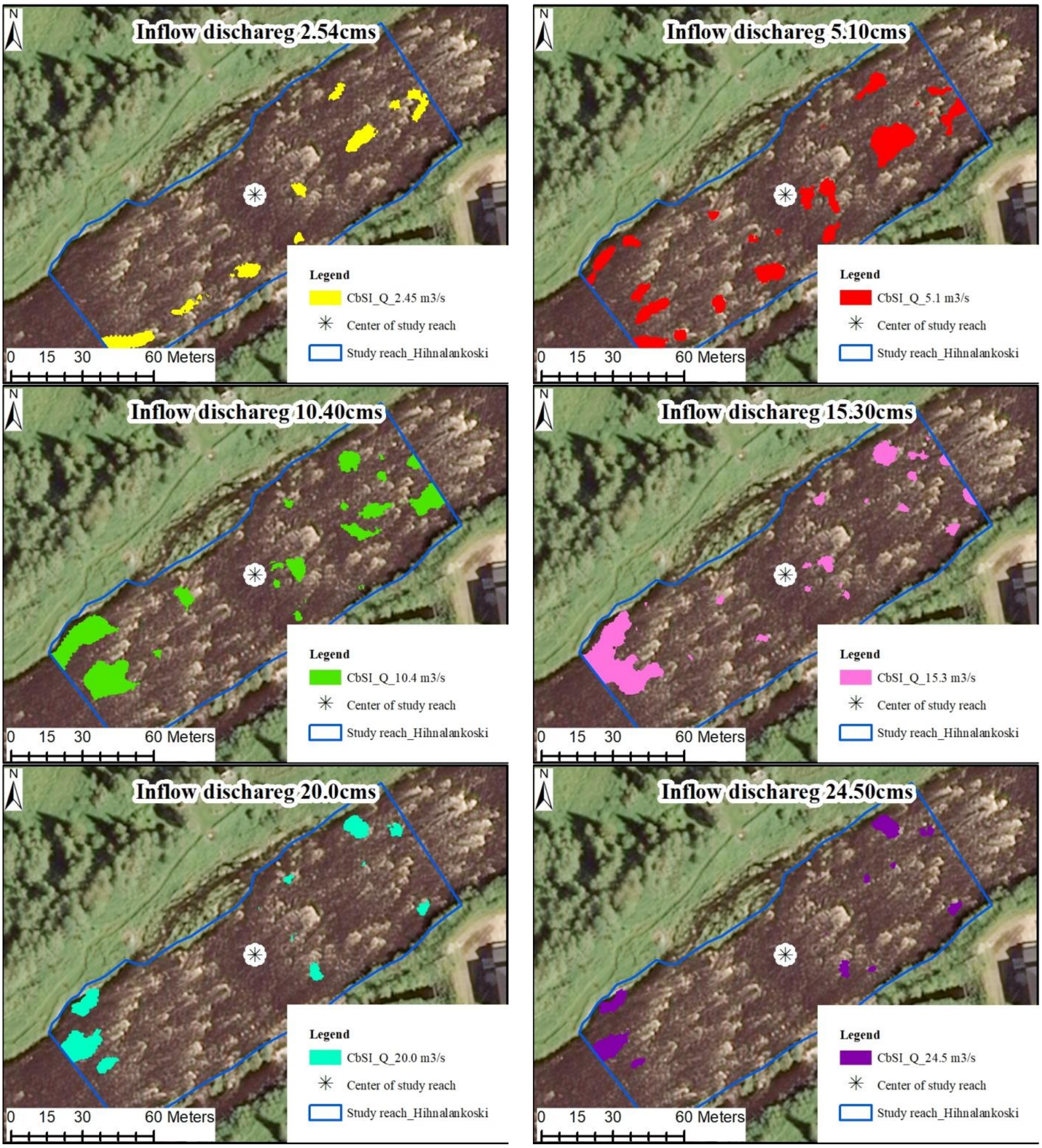


Figure 34 Change in fish habitat location at various discharges at modified Juurikoski for brown trout over 15 cm

4.5 Stranding areas

The stranding areas and potential stranding could be used to describe the quality of fish habitat Juurikoski, modified Juurikoski and Hihnalankoski for all brown trout classes. The stranding area is used in methodology is simply a well suitable area for the fish class at the maximum 24.5 m^3/s which was dewatered at the minimum flow water level at 2.0 m^3/s. The stranding potential measures the percentage of a defined well suitable habitable area that was stranded during a reduction in discharge from maximum to minimum discharge in the hydropeaking hydrograph. At the Juurikoski and modified Juurikoski, the maximum and minimum flows considered for stranding area and stranding potential calculation were 24.5 m^3/s and 2.0 m^3/s respectively. At Hihnalankoski, the maximum and minimum flows considered for stranding area and stranding potential calculations were 17.34 m^3/s and 4.5 m^3/s respectively.

At Juurikoski out of a total of 46,392 m^2 total rapid area studied in this research, approximately 22 % (10,203.4 m^2) is habitable by fish. Out of the 10,203.4 m^2 habitable area the stranding potential for brown trout under 10 cm, between 10 to 15 cm and over 15 cm are 23.2 %, 18 %, and 6.5 % respectively. The standing areas and potentials are distributed around weirs 4C, 4 A&B, 3 A&B, 1A, 1B and 2 A, B&C as shown in table 7 and 8. At Hihnalankoski almost all the entire study area (10,304.4 m^2) are habitable by fish. As shown in Table 9, the stranding potential at Hihnalankoski for brown trout under 10 cm, 10 to 15 cm and over 15 cm was 10.1 %, 5.5 %, and 1.9 % respectively. Also at modified Juurikoski, the stranding potential for brown trout under 10 cm, 10 to 15 cm and over 15 cm was 13.0, 11.5 and 7.4 respectively. The pictures of stranding area at Juurikoski for brown trout under 10 cm, 10 to 15 cm and over 15 cm are displayed in figures 35, 36 and 37. Similarly, for Hihnalankoski for brown trout under 10 cm, 10 to 15 cm and over 15 cm are displayed in figures 38, 39 and 40. Also, pictures of stranding area at modified Juurikoski for brown trout under 10 cm, 10 to 15 cm and over 15 cm are displayed in figures 41, 42 and 43.

Table 7 Stranding areas at Juurikoski.

Weir	Brown trout Stranding area (m^2)		
	Under 10 cm	10-15 cm	over 15 cm
4 C	42.2	13.0	23.5
4 A&B	491.3	286.4	177.0
3 A&B	650.4	537.3	116.3
1 A	11.9	14.8	78.9
1 B	459.1	306.0	0.0
2 A,B&C	710.8	680.5	265.5

Table 8 Stranding potential at Juurikoski

Weir	Brown trout Stranding potential (%) at Juurikoski		
	Under 10 cm	10-15 cm	over 15 cm
4 C	12.8	3.9	7.1
4 A&B	18.7	10.9	6.8
3 A&B	28.3	23.4	5.1
1 A	1.2	1.5	8.1
1 B	42.3	28.2	0.0
2 A,B&C	24.6	23.5	9.2

Table 9 Stranding areas and potential in Hihnalankoski and modified Juurikoski

Brown trout class	Fish stranding area (m^2)		Fish stranding potential (%)	
	Hihnalankoski	Modified Juurikoski	Hihnalankoski	Modified Juurikoski
Under 10 cm	1041.5	1336.5	10.1	13.0
10-15 cm	565.5	1188.9	5.5	11.5
over 15 cm	196.4	766.3	1.9	7.4

Note: Total fish habitable area = 10304.4 m2

Figure 35 Stranding at Juurikoski for brown trout under 10 cm

Figure 36 Stranding at Juurikoski for brown trout under 10 to15 cm

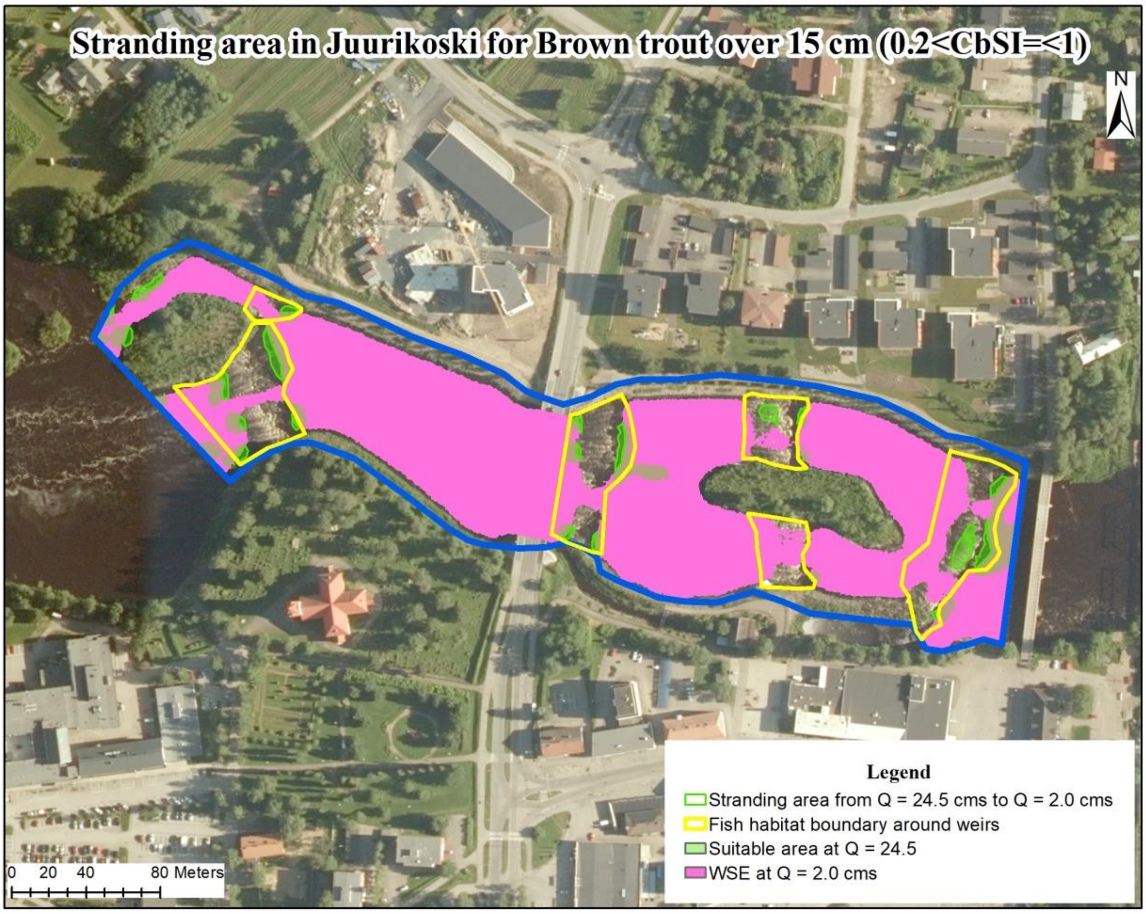


Figure 37 Stranding at Juurikoski for brown trout over 15 cm

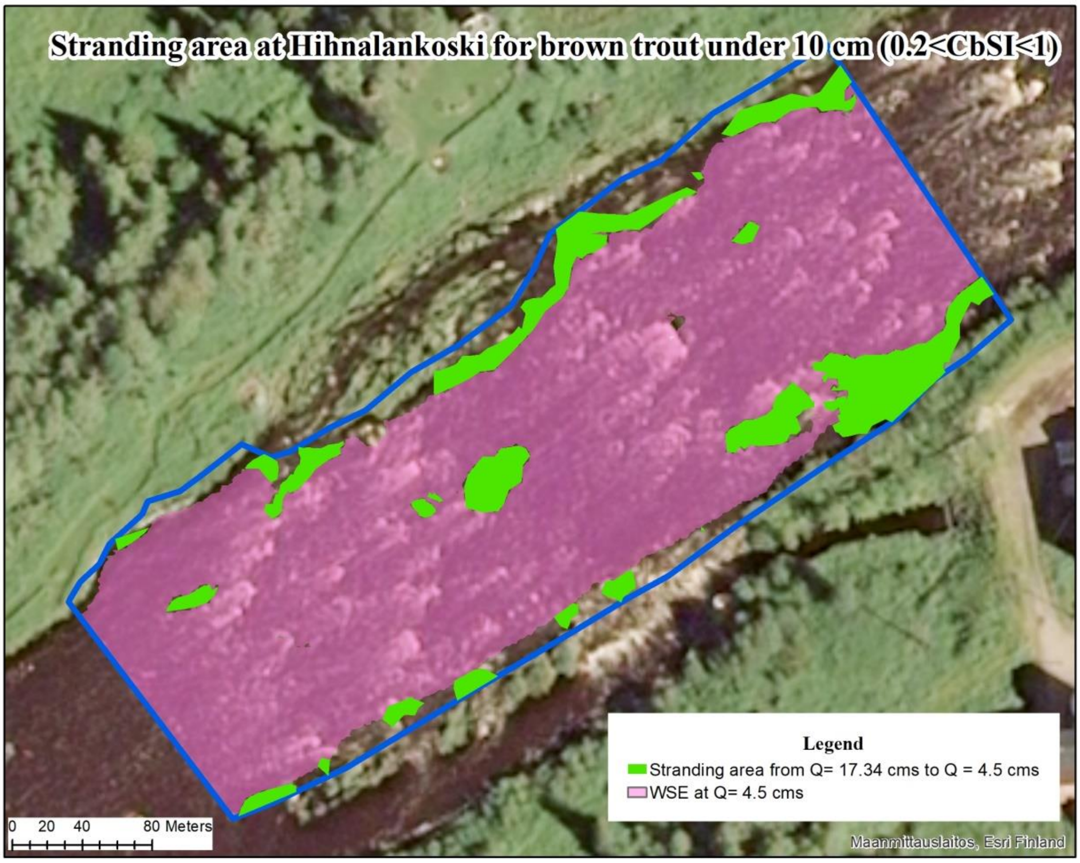


Figure 38 Stranding at Hihnalankoski for brown trout under 10 cm

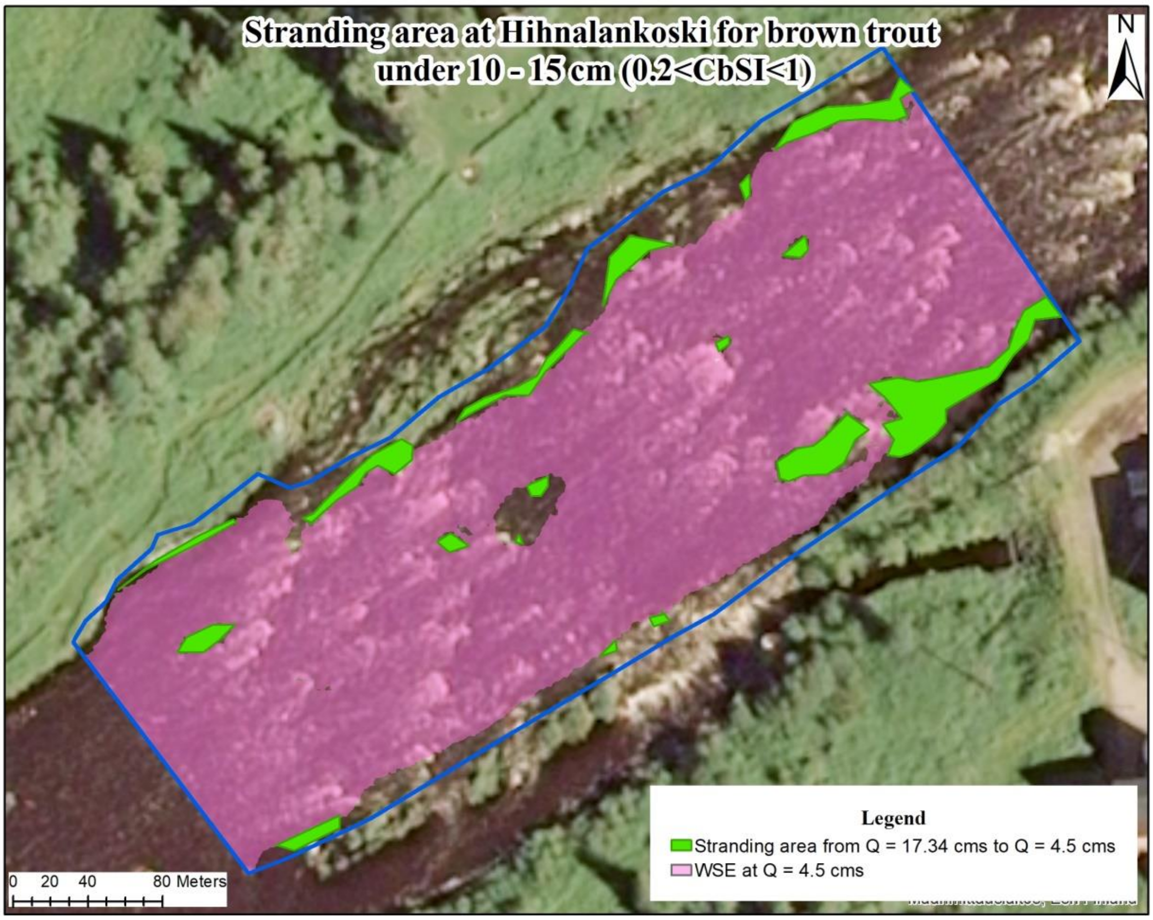


Figure 39 Stranding at Hihnalankoski for brown trout under 10 to 15 cm

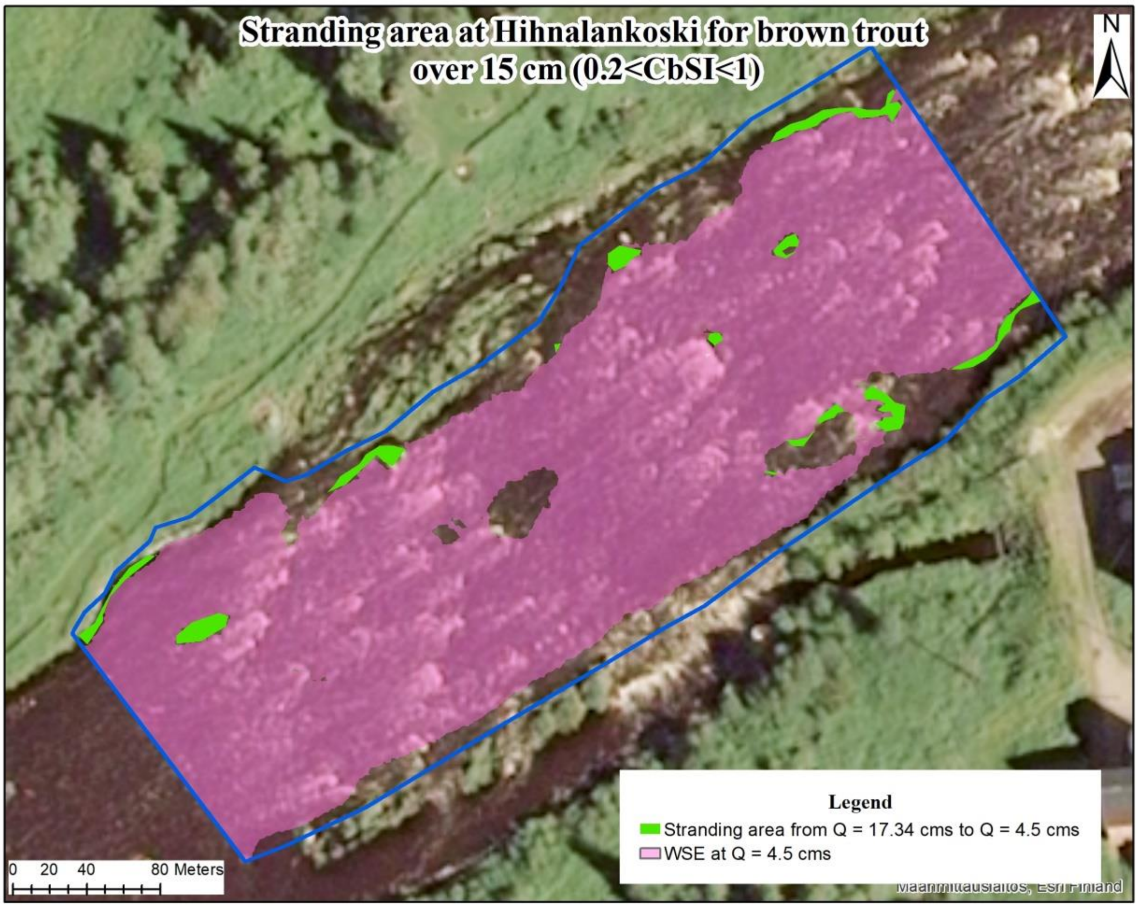


Figure 40 Stranding at Hihnalankoski for brown trout over 15 cm

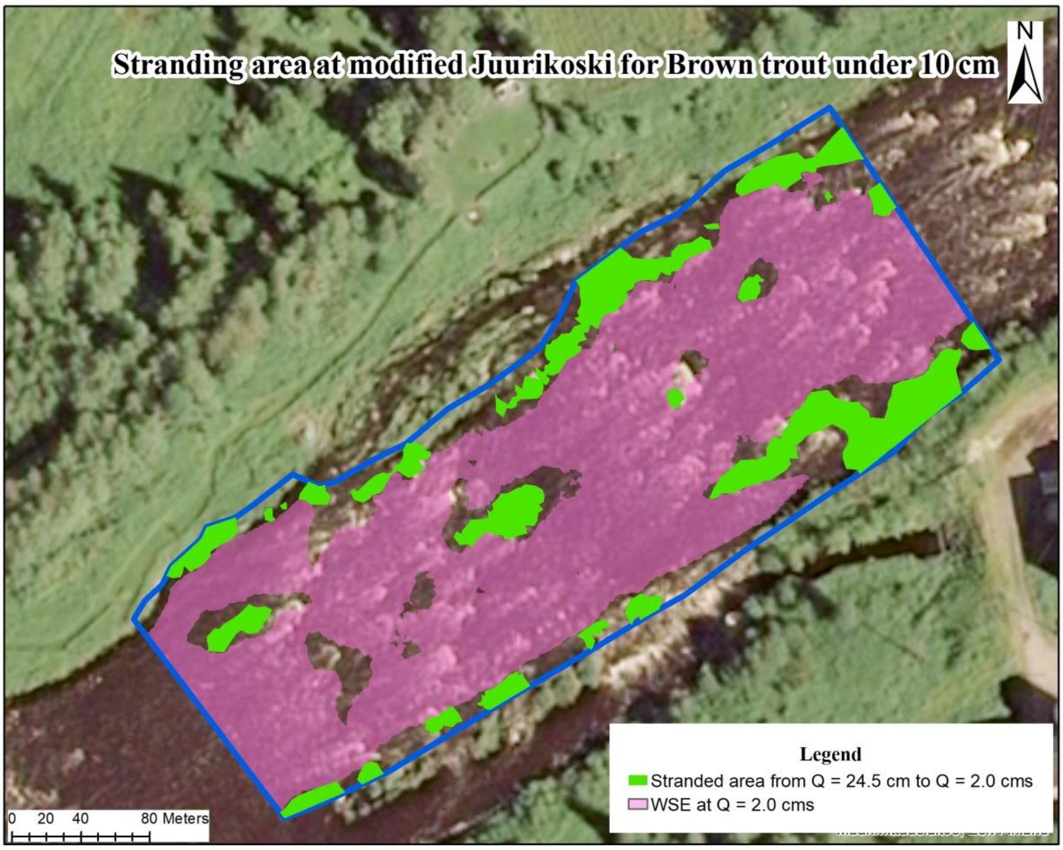


Figure 41 Stranding at modified Juurikoski for brown trout under 10 cm

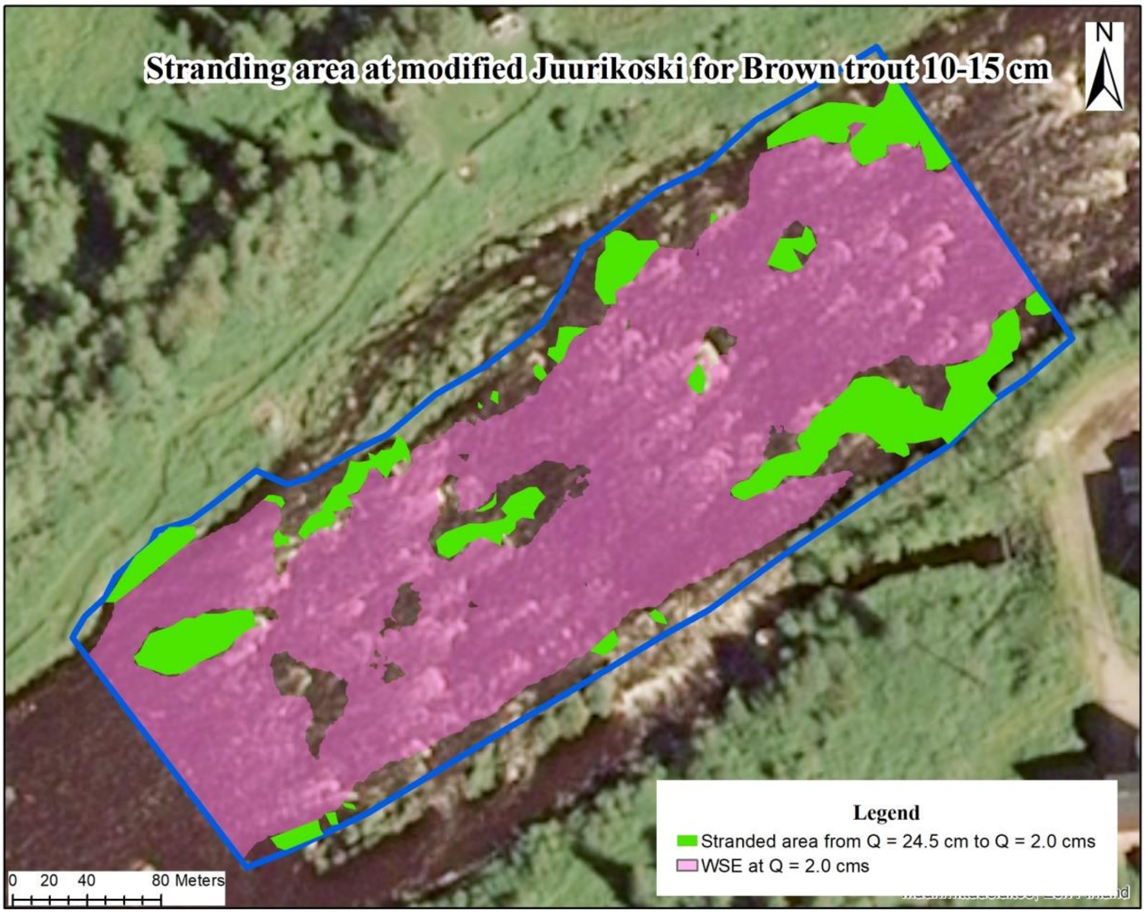


Figure 42 Stranding at modified Juurikoski for brown trout under 10 to 15 cm

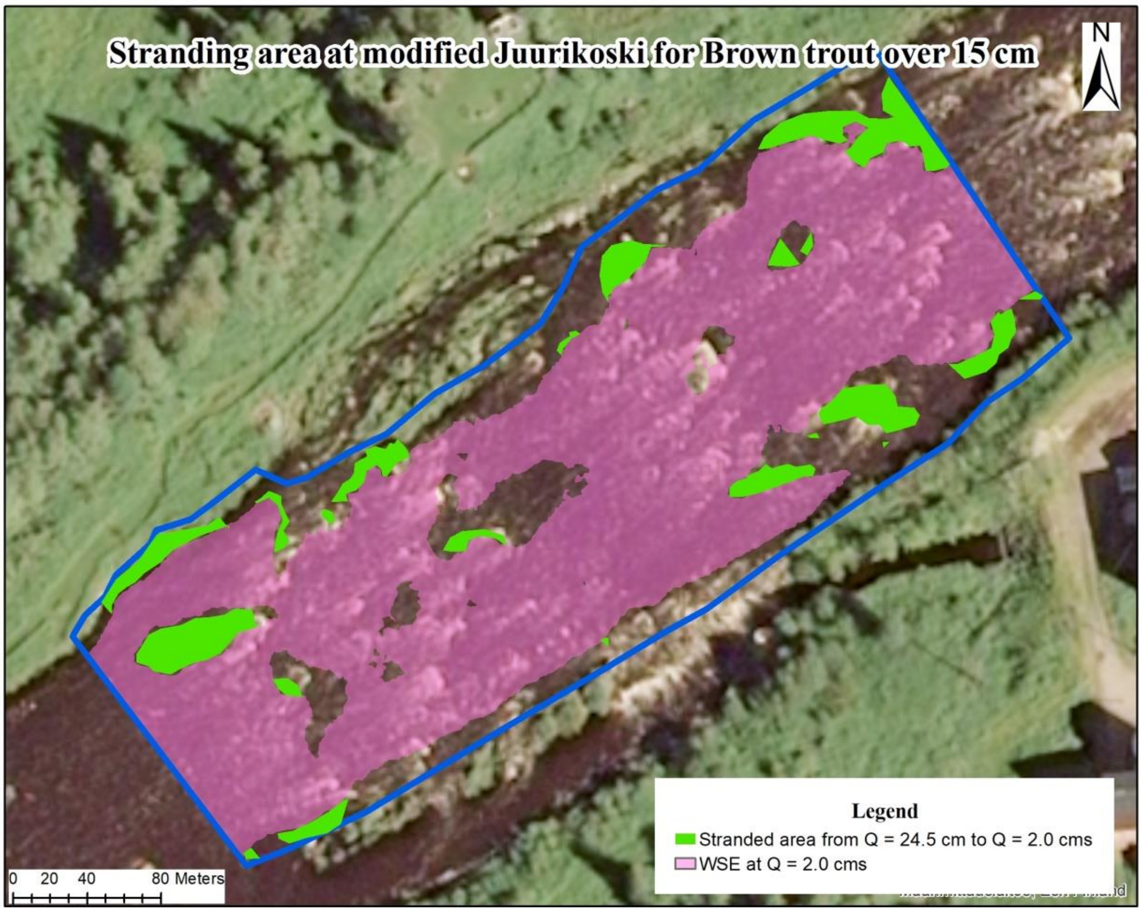


Figure 43 Stranding at modified Juurikoski for brown trout over 15 cm

4.6 Thermopeaking

As shown in figure 44, the responses in water temperature peaks were similar to responses in WSE peaks except at cross-section 900 (see figure 34f). The peak temperatures followed right after lowest WSE in the fluctuation cycle. The average lag time between lowest WSE in the fluctuation cycle and its response in the peaking temperature were 1, 1.3, 6.38, 10.13 and 18.5 hr for cross-sections 37600, 29000, 21800, 14200 and 7700 respectively. The time lag XS-900 even though was not very clear to see, the water temperature decreased slightly below 15 °C after a sharp increase in WSE from 0.2 m to 0.32 m between the 65th and 70th hr (see figure 44 f).

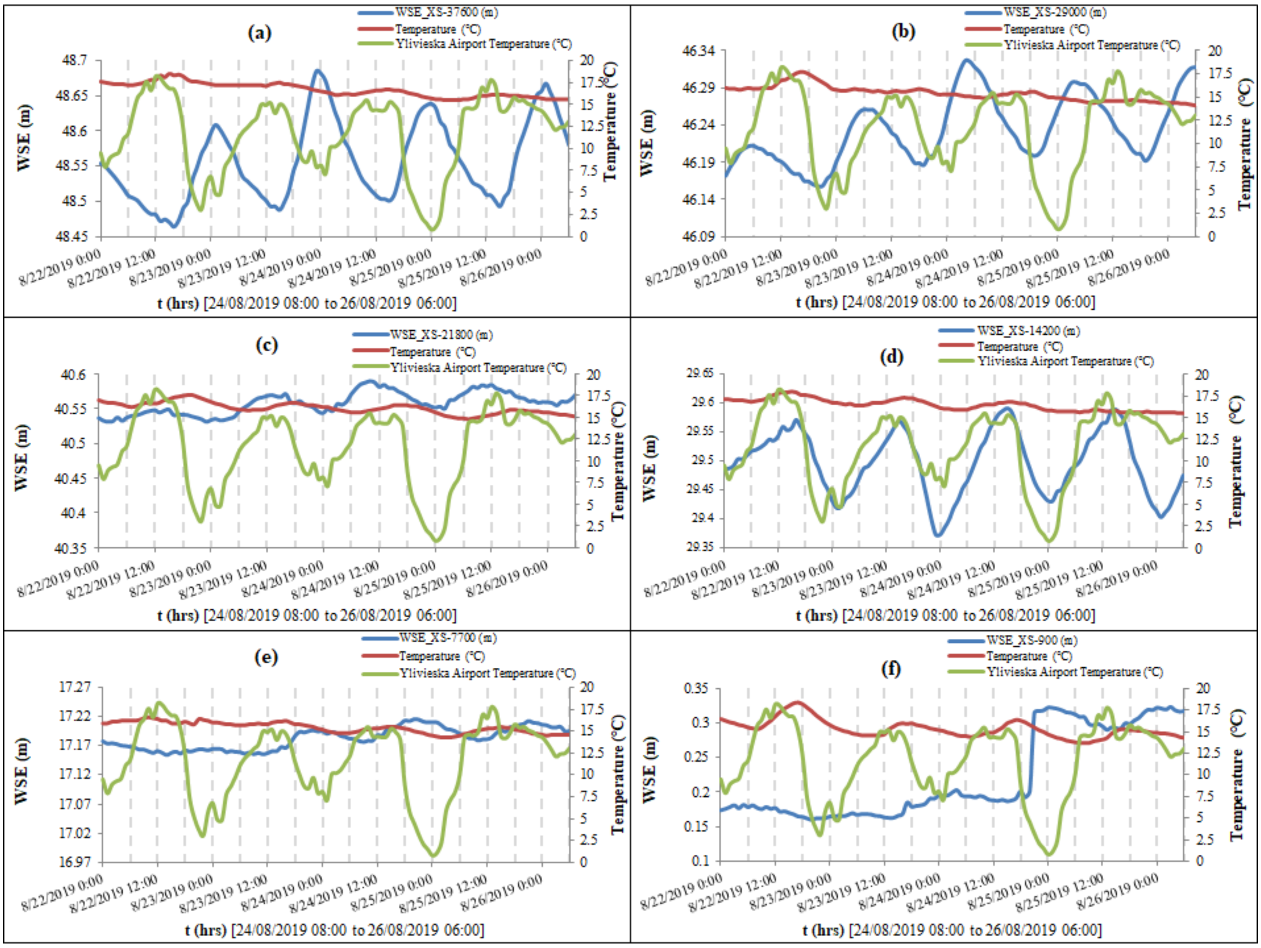


Figure 44 Thermopeaking at defined cross-sections of the lower Kalajoki

Incorporating the local temperature in the same timescale as WSE and water temperature, the results showed the influence of local temperature on water temperature during the day. The peaks in water temperature correspond well with the local temperature during the day time typical around 12 noon.

The results for water temperature response with fluctuations in local temperature in WSE at Hamari and Hihnalankoksi are shown in figures 45 and 46. There was a clear observation of local temperature increasing the water temperature and increased plant flow from Hamari HPP cooling down the water temperature during the day time. In the night water temperature drops but not to the level of local temperature.

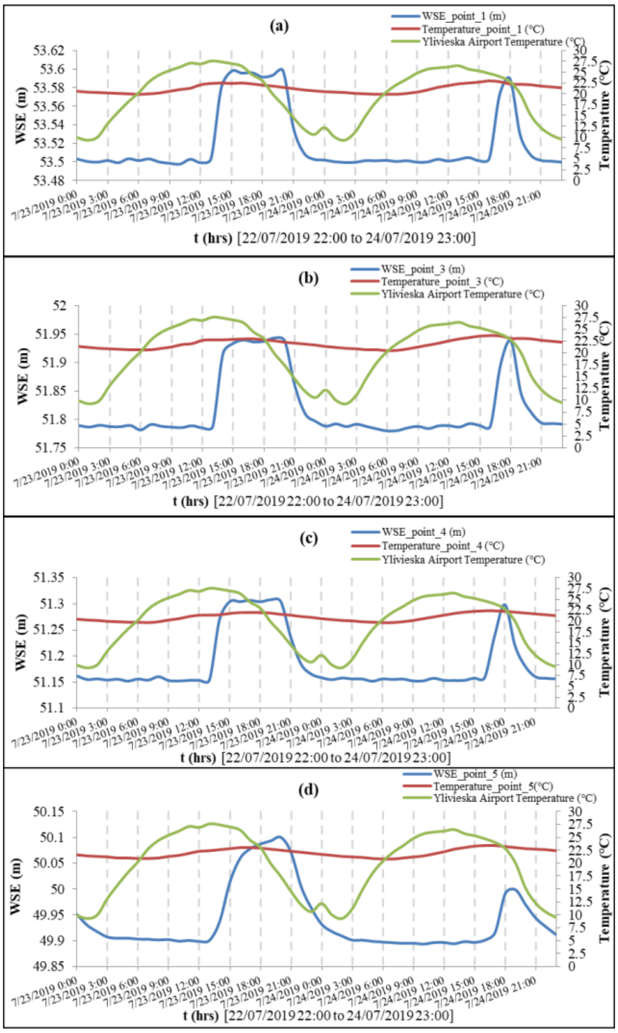


Figure 45 Thermopeaking at Hamari

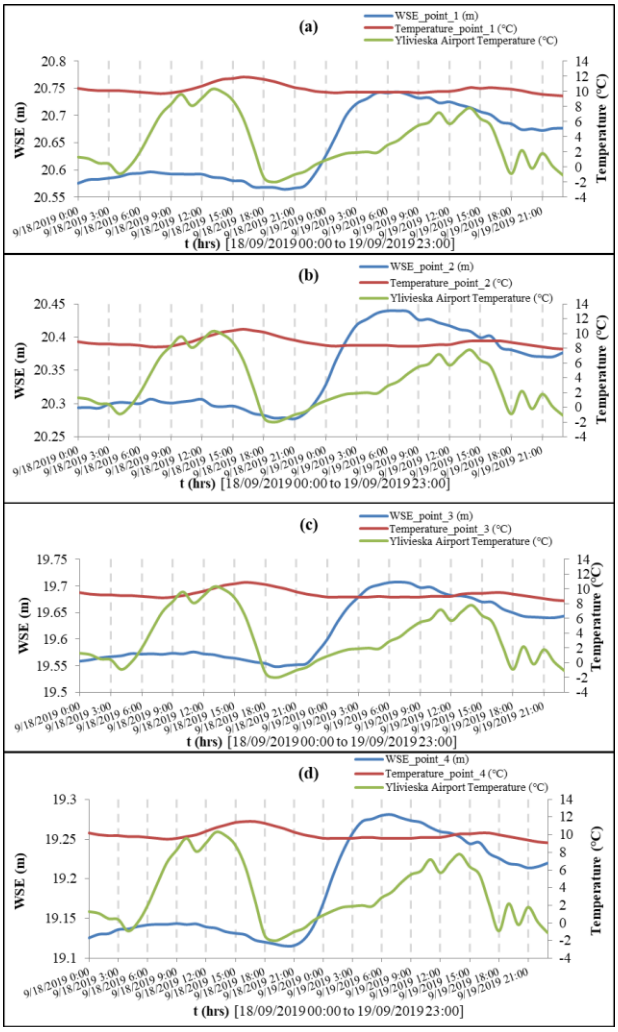


Figure 46 Thermopeaking at Hihnalankoski

5 DISCUSSIONS

5.1 Classification and level of hydropeaking in Kalajoki below Hamari hydropower plant and Niskakoski

Knowledge of the level of hydropeaking within Kalajoki (at the upper reaches including Juurikoski and lower reaches including Hihnalankoski) would be the starting point to substantiate the need for improvement in the ecohydraulic state of the river reaches within the Kalajoki. The results of statistical analysis for hydropeaking classification revealed 'high' class as the hydropeaking indicator (HP1) and ramping rate indicate (HP2) generally exceeded their thresholds with the exception of a wet year in 2015 which gave 'medium' class. It can be concluded based on the hydropeaking classification results that river reaches in the upper parts of lower Kalajoki including Juurikoski is undergoing high-class hydropeaking and therefore there is a need to improve the ecohydraulic state of the river. Ashraf et al. (2018) also reported a high hydropeaking class below Hamari HPP. A high hydropeaking classification confirms the need for mitigation measures to protect and maintain the ecological integrity of the river in a sustainable manner.

The hydropeaking classification at Niskakoski using discharge data for the same period ie (2006 to 2018) showed a generally low hydropeaking class according to the method of Carolli et al. (2015). A comparison of annual average discharge at Niskakoski to Hamari showed a 95% discharge increases on average at Niskakoski. Thus discharge at Niskakoski was on average 95% more than discharge observed at Hamari hydropower plant at the same time resolution. This raised suspicions because based on catchment area difference this cannot be true. It expected that since Niskakoski has more catchment area than the point at the outlet of Hamari HPP, it should have more flow but not that much compared with Discharge from Hamari HPP. It was not clear what could be the reason for the moderate hydropeaking class during the year 2012 at Niskakoski. However, the results suggested the hydropeaking impact on a river Kalajoki dampens in the lower part as more water is collected by the increased catchment area. Later in the study, it was found that due to vegetation growth around the measuring cross-section of the river, data from Niskakoski was faulty and hence the hydropeaking classification was abandoned. At least it was concluded with certainty that Juurikoski was experiencing high hydropeaking that can affect negatively the natural habitats of the river ecosystem (Person, 2013, p.16). For Hihnalankoski a mere conclusion of less impact of hydropeaking from Kalajoki was assumed based site observations.

5.2 Hydropeaking induced water surface elevation fluctuation on downstream reaches of Hamari hydropower plant on the Kalajoki

Hydropeaking creates fluctuations in discharge leading to significant changes in physical conditions of the river in the downstream reaches from a hydropeaking plant. Fluctuations in river velocity and depth at different cross-sections of downstream river reach affect the preferences of different ages of fish and hence the physical habitat of fish species in those rivers. In this study, at river Kalajoki only brown trout preferences in habitat condition were considered. The application of 1D modeling (HEC-RAS) on hydropeaking impacted river reaches downstream of the Hamari HPP presented an opportunity to quantitatively describe how much WSE fluctuates during typical hydropeaking activities in the Kalajoki during summer. The extent to which WSE becomes minimal will give an impression of how far the river physical conditions and fish habitat disturbance due to typical summer hydropeaking from the Hamari HPP get minimal or simply how far it will travel downstream from Hamari HPP.

The results of three typical summer hydropeaking flows showed significant fluctuation in WSE in the downstream reaches of the Hamari HPP. At downstream locations, fluctuations were dampened depending on the magnitude of discharge in the hydropeaking hydrograph. It was clear the high hydropeaking flow created the highest fluctuation travels to the downstream reaches followed by medium then low hydropeaking flows. Vegetation growth is speculated to be the cause of the increased WSE fluctuation at XS-18500 and the Niskakoski gauging station area during high and low hydropeaking flow scenarios. As found by (Chembolu et al., 2019), the presence of vegetation either flexible grass, heterogeneous patches, or mixed vegetation has the ability to reduce the flow velocity which in turn increase water levels (Errico et al., 2018) at the those vegetated sections of the river reach.

During high flow hydropeaking scenario, there was a WSE variation of 29.3 to 9.2 cm within 16.2 km from Hamari HPP whiles medium and low hydropeaking flow scenarios were 15 to 4 cm and 4.5 to 1cm respectively. In the next 21.1 km covering the lower reaches of the 1D model, WSE variation was from 9 to 2 cm for the high hydropeaking scenario, 4 to 1 cm for medium hydropeaking scenario and 3 to 1cm for low flow hydropeaking scenario. The results suggest a high potential of physical habitat changes of brown trout in the upper reaches (within 16.2 km from Hamari HPP) especially for high flow and medium flow scenarios where WSE fluctuation can be in the range from 29.3 to 7 cm. In an extremely high flow event like on 24th October 2019, a WSE fluctuation from more than 50 cm to 10 cm can be expected throughout the entire study with a decreasing WSE the further away the cross-section is located from Hamari HPP. In that case, changes in physical habitat conditions of brown trout can be more severe and will extend very long from the Hamari HPP. The negative river ecosystem effects that can arise from such high WSE fluctuation can be displacement and stranding of juveniles and larvae and from the strong current in the high flow and rapid downramping, flushing away of eggs from the redds, beach and pool stranding of juveniles from fast downramping (Person, 2013). The negative effects can be mitigated through for example the constriction of maximum peak flow (Juárez et al., 2019) and using an appropriate slower upward ramping rate (Auer et al., 2014; Auer et al., 2017; Schmutz et al., 2015). However as already know by Ely-Center through communication from Kimmo Aronsuu, at the river sections below Hamari HPP, most of the riffle areas suitable for brown trouts even in the lowermost 21 km of the river. Therefore based on the results from the 1D modelling, these areas are only slightly affected by hydropeaking with low and medium summer flow. However with high summer flow also the lowermost section is somehow affected from the fluctuating WSE but even with the high hydropeaking flow, the most severe effects are in the section less than 10 km below the Hamarti HPP.

5.3 The impact of the current hydropeaking regulatory practice on the morphological structure of rapids.

The current hydropeaking practice at Juurikoski narrows the river width especially around the weirs when discharge, for instance, fluctuates from say 10.4 to 2.0 m^3/s

changes the shape of the river submerged and unsubmerged areas around the weirs. Thus the effect of the poorly constructed Juurikoski is adding up to the negative impact of current hydropeaking specifically with regards to stranding very bad around especially the totally dried up weirs typically when flows are below 10.4 m^3/s. Thus stranding impact of current hydropeaking in Juurikoski is much dependent on the poor construction of its river morphology (Vanzo et al., 2016b). The weirs openings are forcing the water top width to narrow around the weirs creating total dryness around those dry weirs parts. At the lower-most part of Juurikoski below weir 4, the absence of weirs and the presence of vegetation made the river shape more stable during hydropeaking discharges. Hihnalankoski had a more stable river shape and more morphologically stable rapid compared to Juurikoski during hydropeaking although also a constructed rapids in Finland. The reason for this was the absence of weirs and the fact that the minimum discharge at Hihnalankoski was much more than the minimum allowable environmental flow of 2.0 m^3/s. The bathymetry of Hihnalankoski allowed for much coverage of water and the minimum of 4.43 m^3/s and above which kept the shape of the river firmly stable but with variations in the WSE. Hihnalankoski seemed to have been better reconstructed than Juurikoski. Additionally, Hamari is much closer to the hydropeaking source and hence is expected to experience more sudden fluctuation in WSE than at Hihnalankoski

At this stage, it can be concluded that to reduce the impact of current hydropeaking practice in Juurikoski, reconstruction of the Juurikoski should be seriously considered. This could help increase the diversity of biotic community (Bruder et al., 2016).

5.4 Effect of current hydropeaking practice on fish habitat at Juurikoski and Hihnalankoski

A question of interest to this study was to evaluate how current hydropeaking practices of Hamari hydropower plant affect quantity and quality of fish habitat in the downstream reaches in the Kalajoki catchment specifically at Juurikoski and Hihnalankoski.

According to the current water use permit regulating the use of water by the Hamari HPP, a minimum allowable environmental flow of 2.0 m^3/s is to be observed. Typical

WUA during summer hydropeaking is ranged from 338.25 to 594.54 (m^2 $100m^{-1}$river reach) for brown trout under 10 cm with the maximum WUA at 5.7 m^3/s. For brown trout between 10 to 15 cm it ranged from 330.5 to 496.86 (m^2 $100m^{-1}$river reach) with the maximum WUA at 10.4 m^3/s. For brown trout over 15 cm, it ranged from 414.61 to 519.2 (m^2 $100m^{-1}$river reach) with the maximum at 13.1 m^3/s. At Hihnalankoski typical summer WUA during hydropeaking was much better than at Juurikoski ranging from 762.43 to 1907.38 (m^2 $100m^{-1}$river reach) with the maximum at 4.43 m^3/s for brown trout under 10 cm, 1078.21 to 1674.32 (m^2 $100m^{-1}$river reach) with the maximum at 7.1 m^3/s for brown trout between 10 to 15 cm, and 1140.14 to 1415.35 (m^2 $100m^{-1}$river reach) with the maximum at 7.2 m^3/s for brown trout over 15 cm. Huusko and Yrjänä (1997) during summer measured 151 to 281 (m^2/100 m river reach) for brown trout under 10 cm with the maximum at 2.4 m^3/s, 126 to 168 (m^2/100 m river reach) for brown trout 10 to 15 cm with the maximum at 2.4 m^3/s, and 15 to 48 (m^2/100 m river reach) for brown trout over 15 cm with the maximum at 4.8 m^3/s after restoration of the River Kutinjoki in Finland which had been dredged out in the 1950's for timber production.

In general, it was expected that from the habitat use point of view, the smaller the size of Brown trout would prefer much shallower and slow-moving water whiles larger size trout would prefer faster and deeper parts of the river reach for the purposes of maximizing their net energy intake-rate in searching for food, and shelter as a means of adaptation (Jenkins and Keeley, 2010). In all brown trout size classes, there was a decline in WUA as water depth and velocity fell below the preference for a specific fish class. In the case of Brown trout under 10 cm, the habitable areas got too deep and too fast at discharges from 17.3 to 24.5 m^3/s which were not preferred by brown trout under 10cm hence the loss in WUA at discharges from 17.3 to 24.5 m^3/s. In general, by visual observation of habitat maps, habitat area locations were in the shallow and slow-moving parts (especially around the shallow rockfills around the weir) for the smallest size class of brown trout in this study and grew into the pools for larger size Brown trout of the study reached. The observation was consistent with the general behaviour of habitat use of salmonids found in (Jonsson and Jonsson, 2011, p.67-76). However, the assumption of the perfect substratum in the entire study reach at Juurikoski presents some uncertainty and a possible too optimistic result in the fish habitat areas formed in the pools areas. It was already known by ELY-center that the pools had no suitable substratum. Although an attempt was made to minimize the uncertainty in fish habitat in the pool areas by using the product option instead of geometric mean for WUA computation, there were yet some habitats appearing in the pools which were at least better than the geometric mean option. Thus the geometric mean option showed more habitats in the pools areas than the product option. (Koljonen et al., 2013) on the other hand used the geometric mean because they had estimated river bed substratum River Kiiminkijoki better a modified Wentworth scale by (Vehanen et al., 2010). Even though overhead cover for Brown trout has been found to affect their habit use (Jonsson and Jonsson, 2011, p.77), the preference for the overhead cover was not considered in this study. Based on the results from modeling some caps on discharge can be defined to ensure some minimum significant WUA is always available during hydropeaking. Capping the minimum and maximum hydropeaking flows to 3.0 to 10.4 m^3/s respectively for medium and low summer hydropeaking will ensure at least 500, 400 and 500 (m^2 $100m^{-1}$ river reach). During the high hydropeaking scenario, the river discharge must not exceed 20 m^3/s because beyond this flow there the WUA for brown trout under 10 cm begins to decline below the WUA at 2.0 m^3/s.

5.5 Stranding potential and changes in the position of well suitable habitat location at Juurikoski, modified Juurikoski and Hihnalankoski

The stranding potential on Juurikoski and Hihnanlankoski was a subject of interest for this project because it could lead to mortality of fishes. The task was to ascertain how much area is stranded at Juurikoski and Hihnalankoski and to find out how stranding is affected when the river structure of Juurikoski assumed the river structure of Hihnalankoski.

The stranding areas at Juurikoski for brown trout less than 10, 10 to 15, and more than 15 cm were 23.2, 18, and 6.5 per cent respectively out of a total habitable area of 10,203.4 m^2 from a total study area of 46,392 m^2. The results show that brown trout less than 10 cm and those between 10 to 15 cm would be most affected by stranding than brown trout over 15cm since they have most of their habitat available around those weirs. Saltveit et al. (2001) showed that juvenile brown trout are mostly vulnerable to abrupt discharge reduction during hydropeaking. Additionally, it has been found that juvenile fish are more susceptible to stranding than the adult fishes (Nagrodski et al., 2012; Young et al., 2011; Harby and Noack, 2013). However, the danger of stranding depends on water temperature than just the hydraulic parameters of Juurikoski (Leo et al., 2012). Since Juurikoski is channelized and the bank made more steep with stable large boulders, the case of river bank stranding during hydropeaking would be unlikely to occur. On the other hand, Hihnalankoski had stranding area for brown trout less than 10, 10 to 15, and more than 15cm was 10.1, 5.5, and 1.9 (% per 100m river reach) respectively. Since the banks of Hihnalankoski were more natural than Juurikoski, the stranding areas were more situated in the river banks and in some areas within the river. Modifying Juurikoski with river structure of Hihnalankoski would mean the absence of weirs which would make the morphology of Juurikoski more riverine (Fjeldstad et al., 2012) and would eliminate the stranding area around the weirs. However, the stranding potential areas at the banks would be more pronounced at the river banks due to its close proximity to Hamari HPP and the fact that it would experience rapid changes in discharge due to hydropeaking.

Note that at when Juurikoski is modified with Hihnalankoski, the standing potential increases for all classes of brown trout. To be more specific, standing potential increases by 2.9 %, 6 %, and 5.5 % for brown trout under 10 cm, 10 to 15 cm and over 15 cm respectively. In a situation like that, measures typically related to the use of the right down ramping rate would help to reduce the effect of stranding at the banks but there should be a good balance between the loss in energy production and river ecosystem restoration (Juárez et al., 2019; Kopecki and Schneider, 2016). For example, a slow ramping rate of less than 10 cm h^{-1} has been recommended for trout (Halleraker et al., 2003). Auer et al. (2014) prescribed a day and night time ramping rate of $\leq$6.4 cm/min and $\leq$3.2 cm/min. Notice that night time ramping was much lower because fishes are less active and need more time to sense and relocate their position to avoid stranding. During the beginning of summer when brown tout swims to the upstream waters, it is recommended to as much as possible keep discharge below 240 m^3/s if it can be controlled to prevent pool stranding of upward migrating brown trout (Lascaux and Cazeneuve, 2008) in (Moreira et al., 2018).

From visual inspection, the changes in well suitable habitat area analysis at Juurikoski was much more pronounced than in Hihnalankoski due to the difference in their river morphologies. Due to those pools, well suitable habitats were just limited to the weirs areas considering CbSI from 0.5 to 1. Thus changes in location for brown trout over 15 cm was wider at a maximum of 25 m. For brown trout between 10 to 15 cm suitable moved 16.7 to 83.3 m. For brown trout under 10 cm the suitable habitats were much closer together than brown trout between 10 to 15 cm followed by those above 15 cm. The results suggest habitat changes due to hydropeaking if we consider habitats around the weirs brown trout over 15 cm will be most negatively affected followed by brown trout between 10 to 15 cm then those under 10 cm. However between weirs for all sizes of brown trout would have to travel about 100m or more to find a suitable habitat. In Hinalankoski, changes in habitat location are expected to be much less with less effect on all fishes because of the narrower discharge limits plus the fact that the discharge fluctuation will be more gentle which lead to a more slower change in well suitable habitat location for all brown trout size class.

In general, comparing, Hihnalankoski, modified Juurikoski and Juurikoski, the more vulnerable two are Juurikoski and modified Jurrikoski. Comparing modified Juurikoski to current Juurikoski, changes in location of suitable habitat due to hydropeaking will be more critical for Juurikoski than modified Juurikoski especially considering the effect of those pools. Impacts from issues from thermopeaking and stranding can increase this pressure on the vulnerable fish (brown trout over 15cm). Changing the CbSI to from 0.2 to 1 for the same analysis, as shown in Appendix 15, 16, 17 for brown trout less than 10 cm, 10-15 cm, and over 15 cm, the well suitable habitats don't change much within the weirs but the pools still remain a challenge if any of the fish class has to relocate to find well suitable habitat on other weirs. As shown in Appendix 18, 19 and 20 for brown trout less than 10 cm, 10-15 cm, and over 15 cm, brown trout over 15 cm will have much stress from the change in habitat location followed by 10-15 cm then to less than 10 cm at Modified Juurikoski

5.6 Thermopeaking

As thermopeaking is generally known to put stress on river organisms, finding out how hydropeaking influences thermopeaking along the lower part of the Kalajoki along the 45 rkms stretch and possible effects on Juurikoski and Hihnalankoski could be interesting to know. Initially, the resembling responses in water temperature and WSE fluctuation show evidence of thermopeaking due to hydropeaking but not necessarily the only cause of temperature variation. When the local temperature was included, it could be observed at especially at Juurikoski that the warming of the water during the day time was due to high local temperatures. However, as WSE increased the water temperature declined concluding the effect of cold thermopeaking (Toffolon et al., 2010). During the night, water temperature remained warmer the ambient temperature. It is expected that since Hihnalankoski is located far away from the Hamari HPP, thermopeaking will be much more at Juurikoski than at Hihnalankoski. Thus the peaks in discharge when much dampened takes more time to rise and fall at Hihnalankoski prolonging warming and cooling of water which will reduce the stress on the fishes. Focusing on Juurikoski as the most vulnerable fish habitat site for thermopeaking, it can be concluded that day time cold thermopeaking can be present therefore it must be taken into account that the juvenile fishes could move to more shallower places that can make them vulnerable to stranding from rapid drawdown (Schmutz and Sendzimir, 2018, p.100-101) hence an appropriate downramping rate would help avoid stranding as mentioned in previous chapters. Additionally, fluctuation in WSE and water temperature could negatively affect the growth of juvenile brown trout.

5.7 Structural restoration success at Juurikoski with river structure of Hihnalankoski.

Since morphological of the river plays a key role of creating the habitat diversity and a refuge for biotic community, it is important to compare between Hihnalankoski and Juurikoski which would serve the purpose of creating habitat diversity and a refuge for biotic community than which.

It is already known that the pools in Juurikoski have no substratum than can inhabit fishes. Considering that about 78 % of the Juurikoski is made up of those monotonous pools it will not be able to support fish habitat and therefore cannot create habitat diversity and a refuge for the biotic community (Bruder et al., 2016). Hihnalankoski, on the other hand, had more heterogeneous morphology with no pools or weirs and better coverage of water even at low and possible better habitat for the biotic community than Juurikoski. Based on this comparison it can be concluded that Juurikoski needs to be reconstructed to restore all lost habitats in the pools. However, the issue of ice protection must be taken into account when carrying out the restoration. Restructuring Juurikoski with the river structure of Hihnalankoski will not eliminate the high risk of stranding, thermopeaking, flushing away of larvae, eggs and redds at Juurikoski due to its close proximity to the Hamari HPP. An appropriate operational measure regards but not limited to minimum flow, downward ramping rate suggested by different authors mentioned in previous discussion chapters should be considered to mitigate the possible negative impacts of hydropeaking. It has been shown from table 9 that when Juurikoski is modified with the structure of Hihnalankoski, the fish stranding potential increases for all brown trout class hence the need to add some realistic operational measures to help curtail the destructive effect of hydropeaking on fish habitat at Juurikoski. (Yrjänä, 2004) and (Koljonen, 2011) have both worked on the restoration of dredged rivers in Finland. Schmutz et al. (2015) ramping rates <0.25 cm/min increasing the chances of achieving higher ecological status in a that looks more natural like Hihnalankoski and hence could be good for modified Juurikoski.

5.8 Limitations of models, uncertainties and sources of error in project

The distance and interpolation between transects to perform WSE calculations present a limitation of creating a river bathymetry that could ignore the true shape river shape of the Kalajoki. However, the calibration and validation of the model minimizes the error and bring the model close to reality. The calibration of the model around Niskakoski presented challenges as modeled WSE was lower than observed WSE for all reasonable roughness. The presence of a lot of river vegetation in those sections could be the cause of this behaviour. Thus vegetation could be creating some damming effect which raises the WSE above what the model can possibly calculate for all reasonable ranges of manning numbers. Since these claims were not thoroughly verified are just speculations that need scientific verification. Probably more measured cross-section at those reach would help solve the uncertainties in WSE at those sections.

The calibration of the 1D model with low hydropeaking flow scenario and validation with medium and high hydropeaking flow scenarios yielded results which raise questions of uncertainties of the 1D model as usually it's expected that the calibrated model should validate other flows (medium and high hydropeaking flow scenarios). It was obvious that the 1D model required different manning numbers and weir coefficients to properly get the simulated WSE close enough to the observed WSE at the chosen cross-sections. The low flow calibrated 1D HEC-RAS model was not reliable for high flow hydropeaking. Similarly, high flow calibrated 1D HEC-RAS model was not reliable for low flow hydropeaking. This limitation is likely due to the general problem with simulating unsteady flows through pools and rapids described by Brunner (2014). Care must be taken when using the 1D HEC-RAS model set up for this project for any WSE calculations. Also, the models timing problems limit the use of the model to simulate water levels alone because the results will be unreliable. Thus the 1D model was not able to correctly produce the timing of the observed WSE. For daily variation in WSE, it could be reliable.

Two-dimensional 2D habitat models do not estimate fish density in the river but rather helps to ascertain the possibility of fish species to inhabitat it. Although simulation errors have been found to be associated with the simulation of hydrodynamic habitat models, they are generally accurate in predicting fish habitat (Waddle, 2010) analyzing habitat responses in various different flows (Koljonen, 2011). The major question that comes to mind when viewing the results of this work is "How real are the results when compared with observed data?" Although the predictive accuracy of 2D hydrodynamic habitat models in this project has not been verified with actual observed measurement of fishes, it could be trusted that methodology can be reliable (Waddle, 2010).

The erroneous and unreliable discharge data from Niskakoski due to faulty measurements necessitated the development of rating curve at the start and end cross-sections of the 2D fish hydrodynamic habitat based on the discharges computed by the

HEC-RAS 1D at those two sections. The uncertainties and error in the 1D model could transfer into the results of habitat simulations. Extrapolation and interpolation used to generate water levels data outside of the measured data could lead to errors and some uncertainties in the final conclusion of the work. In general, the sources of errors in this project could be human induced errors from field elevation and WSE measurements plus modeling errors.

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The effect of hydropeaking in the lower Kalajoki has been studied and the state of hydropeaking below Hamari was estimated by measurements and modeling. The hydropeaking induced fluctuations in water surface elevation have been analyzed through modeling. The quantity and quality of brown trout habitat at Juurikoski and Hihnalankoski were evaluated. The major findings of this research are as follows.

This study has shown that the fluctuations in WSE elevation and their effect on aquatic ecosystem depend very much on discharge magnitudes in the hydropeaking hydrograph. In typical summer high to medium hydropeaking flow, a WSE fluctuation from 29 to 4 cm can be expected within the 16.2 km below Hamari HPP. Additionally, it has been shown that in very high hydropeaking flow as observed around late October to early November 2019, fluctuation WSE fluctuations from 50 to 10 cm can be expected from the upper to the lower reaches with severe ecological consequences in reaches with larger WSE variations.

The state of hydropeaking below Hamari HPP has been found to be high and therefore needs improvement in the ecohydraulic state of the river. The current hydropeaking practise had a more negative effect on the quantity and quality of brown trout habitat at Juurikoski than Hihnalankoski partly due to the nearness of Juurikoski to the Hamari HPP and also partly due to its poor river construction compared to Hihnalankoski. The large monotonous pools, large changes in location of suitable habitat (at CbSI from 0.5 to 1) during hydropeaking, the significant dewatered areas around the weirs and cold thermopeaking at Juurikoski justifies its poor ecohydraulic state. From a river restoration point of view, it can be concluded that Hihnalankoski was restored much better and hence has a better ecohydraulic state to support river ecosystem. Restoring Juurikoski with the river structure of Hihnalankoski will help improve brown trout habitat quantity in excess of 200 % for all classes of brown trout. However, the morphological restoration alone cannot ensure total eradication of negative hydropeaking effects. Modifying Juurikoski with river structure of Hihnalankoski, stranding potential increases by 2.9, 6 and 5.5 % for brown trout under 10 cm, between 10 to 15 cm and over 15 cm respectively. Therefore in addition to morphological restoration, appropriate operational measures regarding minimum flow adjustment, downramping rate, an adjustment in maximum allowable peak flows should be considered to help mitigate other unavoidable impacts such as stranding and flushing away of larvae, eggs and redds. The findings in this study are significant to help start-up discussions regarding revision of the water use license in operation currently and to help find sustainable solutions to protect river ecosystem at lower Kalajoki. As an operational rule, capping the minimum and maximum hydropeaking flows to 3.0 to 10.4 m^3/s respectively at typical medium and low summer hydropeaking flows will ensure at least 500, 400 and 500 (m^2 $100m^{-1}$ river reach). During high hydropeaking scenario, the flow must not exceed 20 m^3/s because beyond this flow there the WUA for brown trout under 10 cm begins to decline below the WUA at 2.0 m^3/s.

6.2 Recommendation for future work

More cross-sections in the Niskakoski area would help reduce the uncertainties in the 1D model results around the Niskakoski area. The 2D fish habitat model reliability verified with calibration data from electrofishing data or other fish sampling method. It is clear that there is a need for a revision in the water use permit for water use by the owners of Hamari HPP to find more sustainable WSE fluctuation limits. However, to do this other morphological measures should be considered. It is important for the substratum to be measured in order to eliminate the uncertainty of perfect substratum assumption. Since the literature review did not show thresholds for brown trout or any other fish species in Finland with regards to ramping rate limits it will be important to study what down and upward ramping rates are used by the owner of Hamari hydropower plant and compare with those found by literature. Since River 2D was not developed for rivers with the hydraulic structures, there were challenges with calibration and validation of the 2D model hydraulic model. It will be good to see how other softwares capable of handling river structures in hydraulic simulation like HEC-RAS 2D affect the results gotten at Juurikoski.

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APPENDICES

Appendix 1 Depth preference for brown trout

Depth preference for Brown Trout [Taimen]								
Taimen <10 cm			Taimen [10-15 cm]			Taimen >15 cm		
#	**depth**	**Preference**	#	**depth**	**Preference**	#	**depth**	**Preference**
1	**5**	0.36	1	**5**	0.29	1	**5**	0.00
2	**15**	0.82	2	**15**	0.37	2	**15**	0.09
3	**25**	**1.00**	3	**25**	0.59	3	**25**	0.28
4	**35**	0.67	4	**35**	0.67	4	**35**	0.63
5	**45**	0.49	5	**45**	**1.00**	5	**45**	0.68
6	**55**	0.30	6	**55**	0.87	6	**55**	0.87
7	**65**	0.09	7	**65**	0.37	7	**65**	**1.00**
8	**75**	0.00	8	**75**	0.19	8	**75**	0.89
9	**85**	0.00	9	**85**	0.04	9	**85**	0.33
10	**95**	0.00	10	**95**	0.00	10	**95**	0.10
11	**105**	0.00	11	**105**	0.00	11	**105**	0.00

Appendix 2 Velocity preference for brown trout

Velocity preference for brown Trout [Taimen]								
Taimen <10 cm			Taimen [10-15 cm]			Taimen >15 cm		
#	**velocity**	**Preference**	#	**velocity**	**Preference**	#	**velocity**	**Preference**
1	**5**	0.90	1	**5**	0.40	1	**5**	0.38
2	**15**	**1.00**	2	**15**	0.53	2	**15**	0.52
3	**25**	0.97	3	**25**	0.75	3	**25**	0.74
4	**35**	0.82	4	**35**	0.90	4	**35**	0.78
5	**45**	0.79	5	**45**	**1.00**	5	**45**	**1.00**
6	**55**	0.64	6	**55**	0.84	6	**55**	0.78
7	**65**	0.48	7	**65**	0.58	7	**65**	0.62
8	**75**	0.25	8	**75**	0.37	8	**75**	0.33
9	**85**	0.12	9	**85**	0.16	9	**85**	0.17
10	**95**	0.06	10	**95**	0.10	10	**95**	0.12
11	**105**	0.01	11	**105**	0.03	11	**105**	0.04

Appendix 3 Substrate preference for brown trout

Substrate preference for brown trout [Taimen]								
Taimen <10 cm			**Taimen [10-15 cm]**			**Taimen >15 cm**		
#	**substrate**	**Preference**	#	**substrate**	**Preference**	#	**substrate**	**Preference**
1	**1**	1	**1**	**1**	1	**1**	**1**	1
2	**2**	1	**2**	**2**	1	**2**	**2**	1
3	**3**	1	**3**	**3**	1	**3**	**3**	1
4	**4**	1	**4**	**4**	1	**4**	**4**	1
5	**5**	1	**5**	**5**	1	**5**	**5**	1
6	**6**	1	**6**	**6**	1	**6**	**6**	1
7	**7**	1	**7**	**7**	1	**7**	**7**	1
8	**8**	1	**8**	**8**	1	**8**	**8**	1
9	**9**	1	**9**	**9**	1	**9**	**9**	1
10	**10**	1	**10**	**10**	1	10	**10**	1

Appendix 4 Visual inspection at rapid 2A, 2B and 2C during 2.5m3/s minimum flow

Appendix 5 Visual inspection at rapid 3A and 3B during 2.5m3/s minimum flow

Appendix 6 Visual inspection at rapid 1B during 2.5m3/s minimum flow

Appendix 7Visual inspection at rapid 4A and 4B during 2.5m3/s minimum flow

Appendix 8 Visual inspection at rapid 4C during 2.5m3/s minimum flow

Appendix 9 Single large circular pipe connecting water from upstream to downstream side channel through the inoperative Old Flour Mill

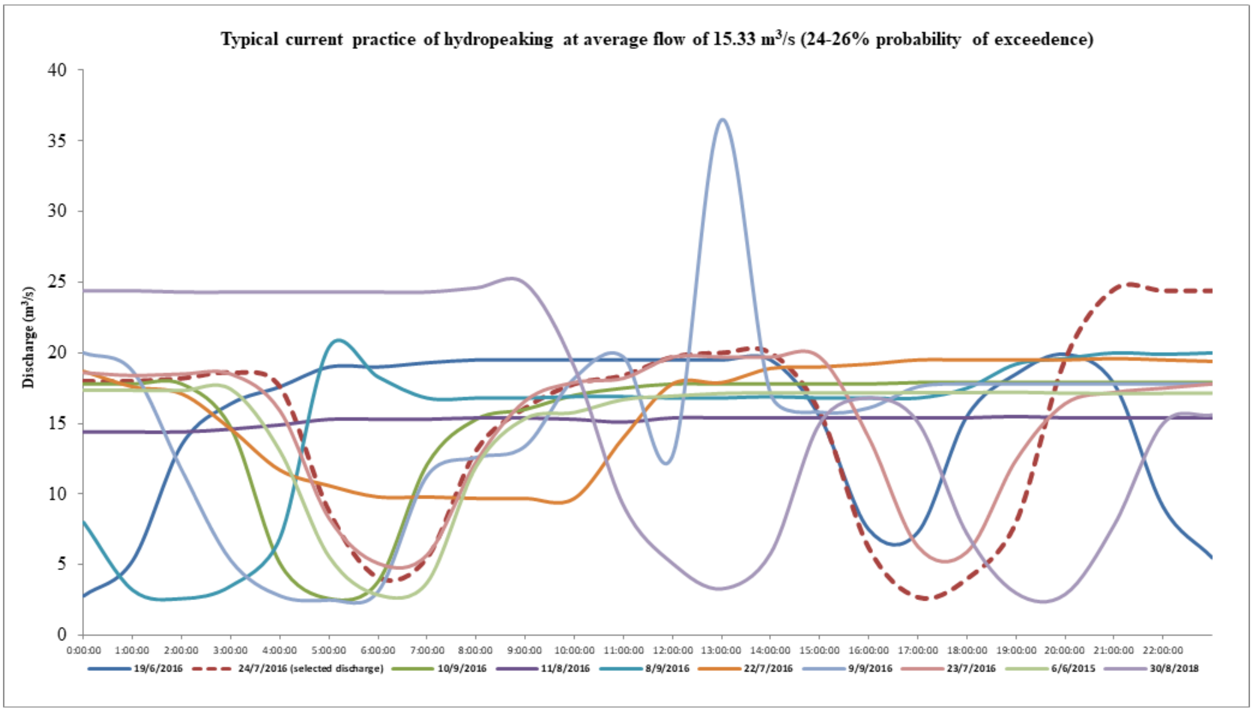
Appendix 10 A view of downstream of side channel looking at the water outlet from old flour Mill.

Appendix 11 View of Hihnalankoski showing submergence in water during field inspection

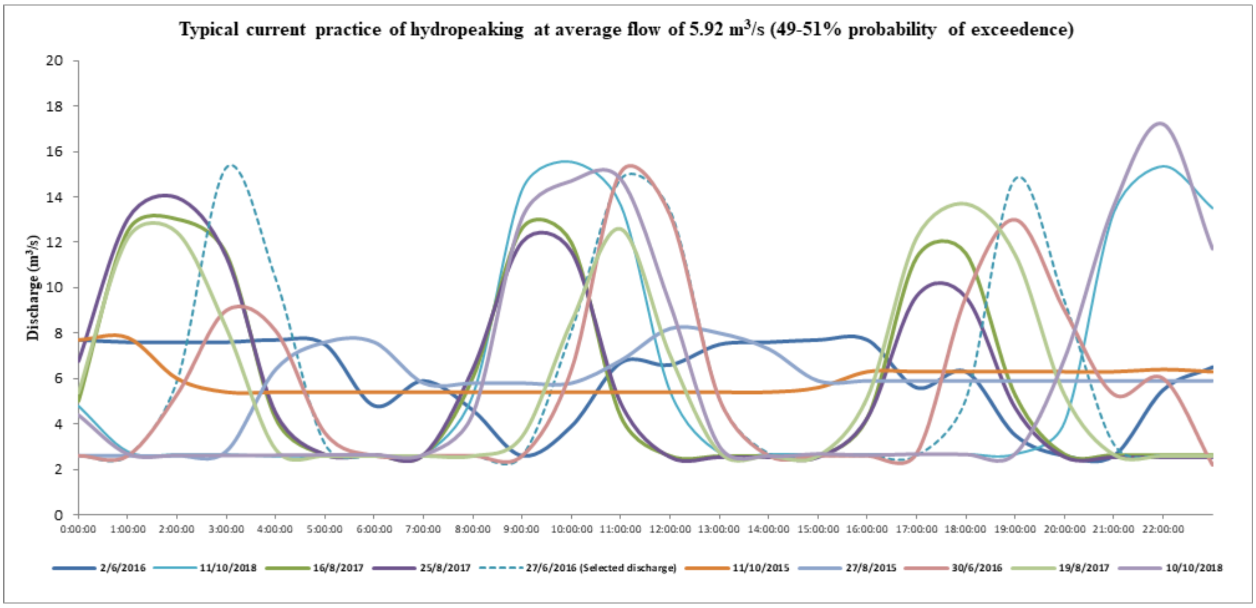
Appendix 12 Moss observed in riverbed at Hihnalankoski during field inspection

Appendix 13 Newly hatched fishes observed at Hihnalankoski during field visit

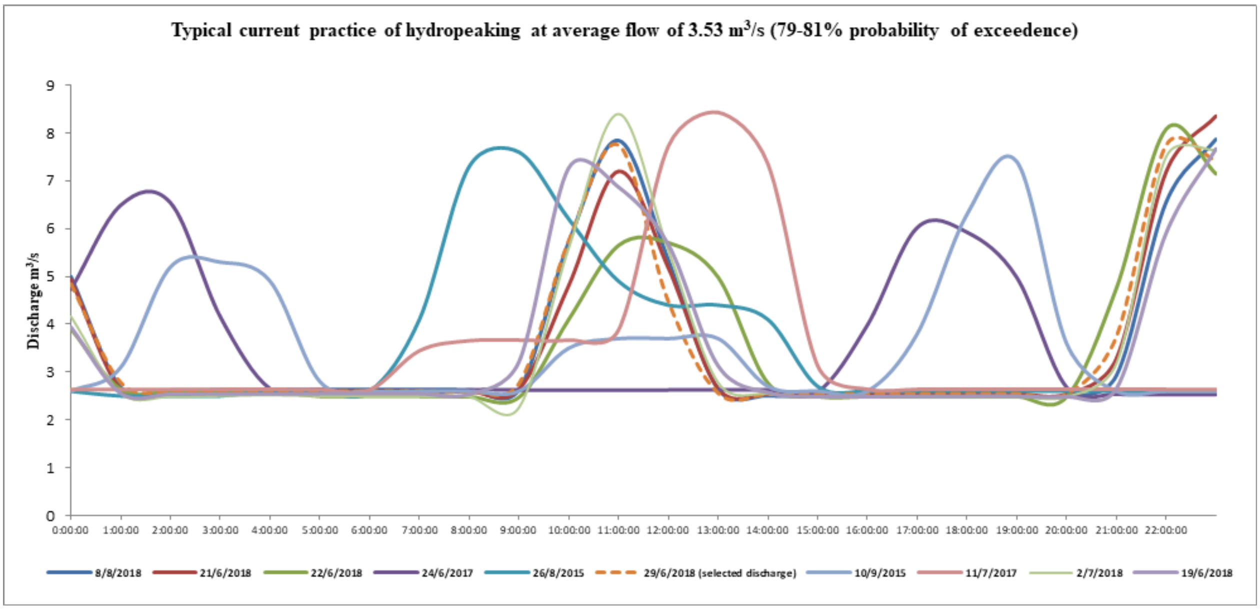
Appendix 14 Typical summer high hydropeaking scenario



Appendix 15 Typical summer medium hydropeaking scenario



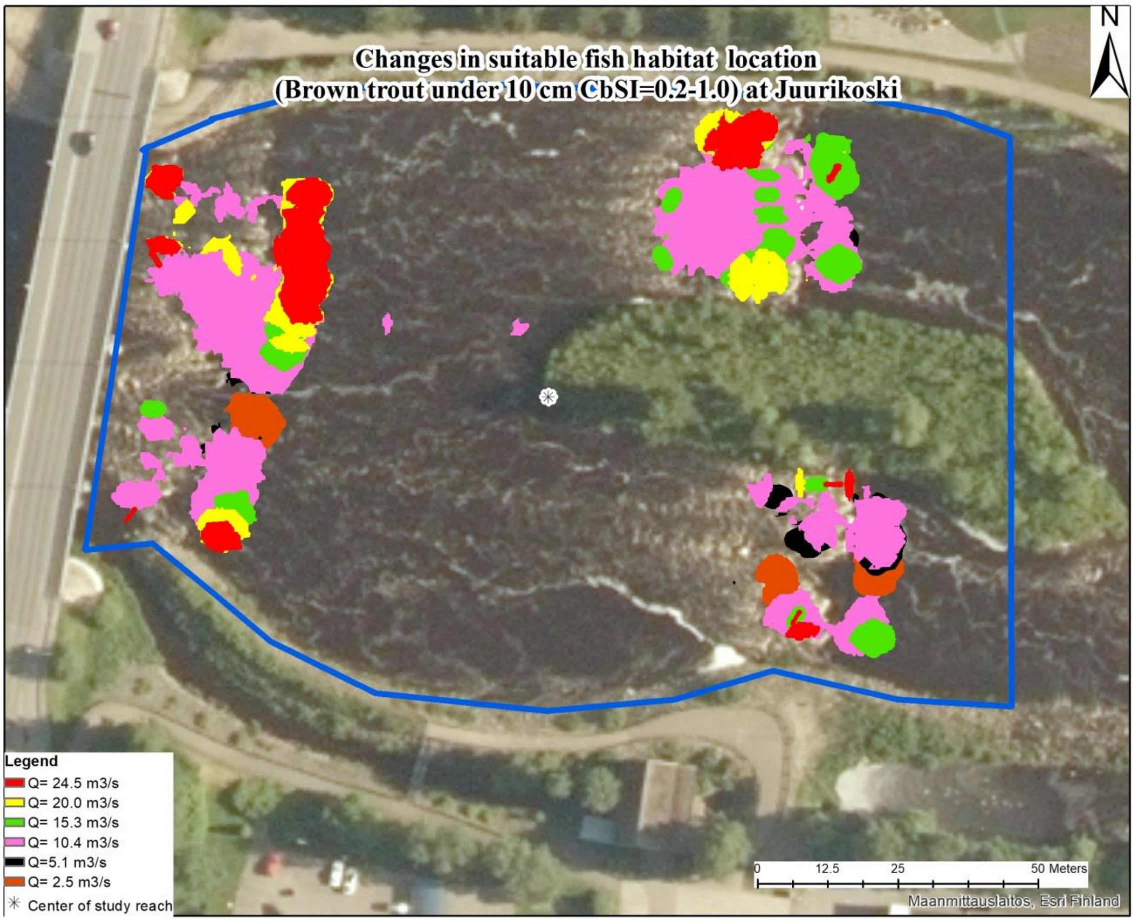
Appendix 16 Typical summer low hydropeaking scenario



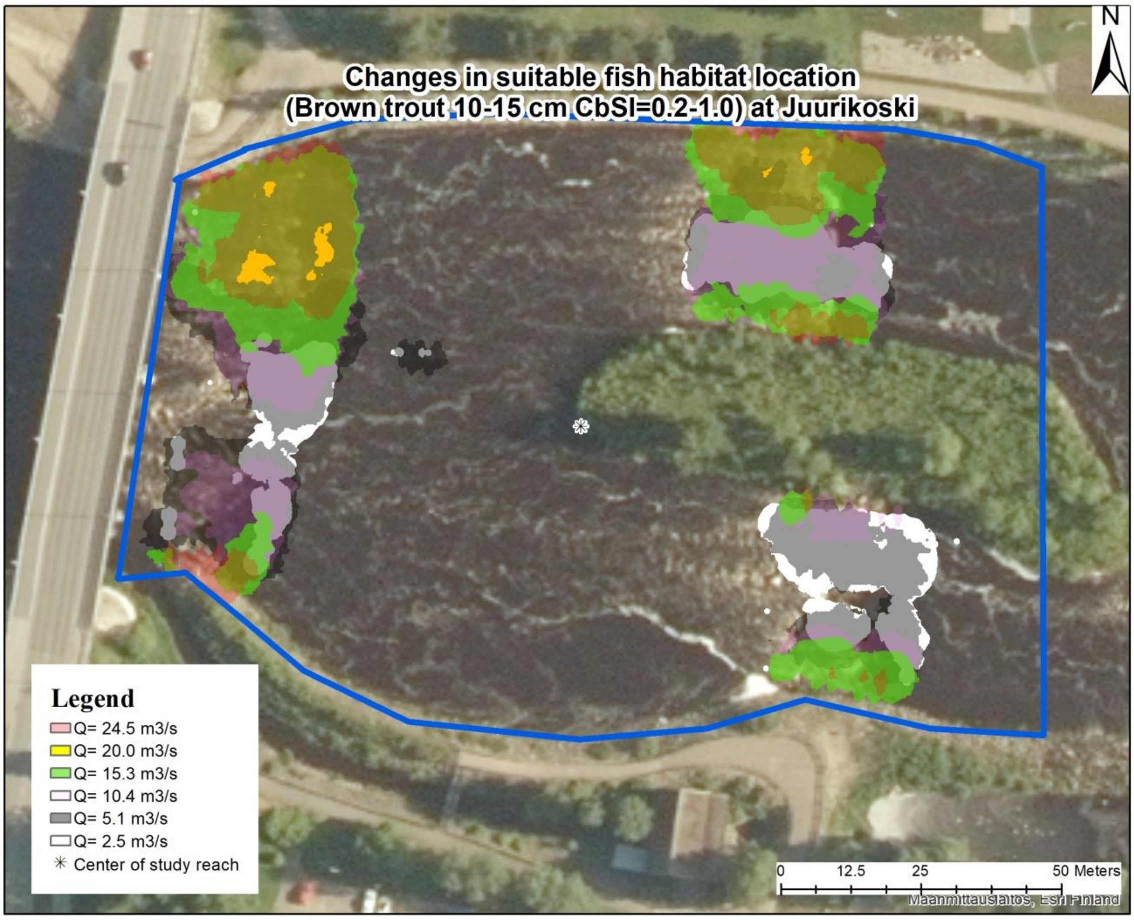
Appendix 14 Selected typical Summer hydropeaking hydrograph and dates from Hamari HPP

	Hydrological data		
	15.33m³/s	**5.92m³/s**	**3.53m³/s**
Time (daily hr)	24/7/2016	27/6/2016	29/6/2018
0:00	**18**	**2.6**	**4.84**
1:00	**18**	**2.6**	**2.78**
2:00	**18.2**	**5.9**	**2.59**
3:00	**18.6**	**15.3**	**2.59**
4:00	**17.6**	**10.4**	**2.6**
5:00	**8.8**	**3.1**	**2.6**
6:00	**4.1**	**2.6**	**2.6**
7:00	**5.5**	**2.6**	**2.6**
8:00	**13.1**	**2.6**	**2.59**
9:00	**16.1**	**2.6**	**2.76**
10:00	**17.8**	**8.1**	**5.75**
11:00	**18.4**	**14.8**	**7.75**
12:00	**19.7**	**13.4**	**4.48**
13:00	**20**	**5.1**	**2.56**
14:00	**20**	**2.7**	**2.54**
15:00	**15.8**	**2.6**	**2.54**
16:00	**6.2**	**2.6**	**2.54**
17:00	**2.7**	**2.6**	**2.55**
18:00	**4**	**5.1**	**2.55**
19:00	**8**	**14.8**	**2.55**
20:00	**19.5**	**9.4**	**2.54**
21:00	**24.5**	**3.1**	**3.74**
22:00	**24.4**	**2.6**	**7.75**
23:00	**24.4**	**2.6**	**7.42**

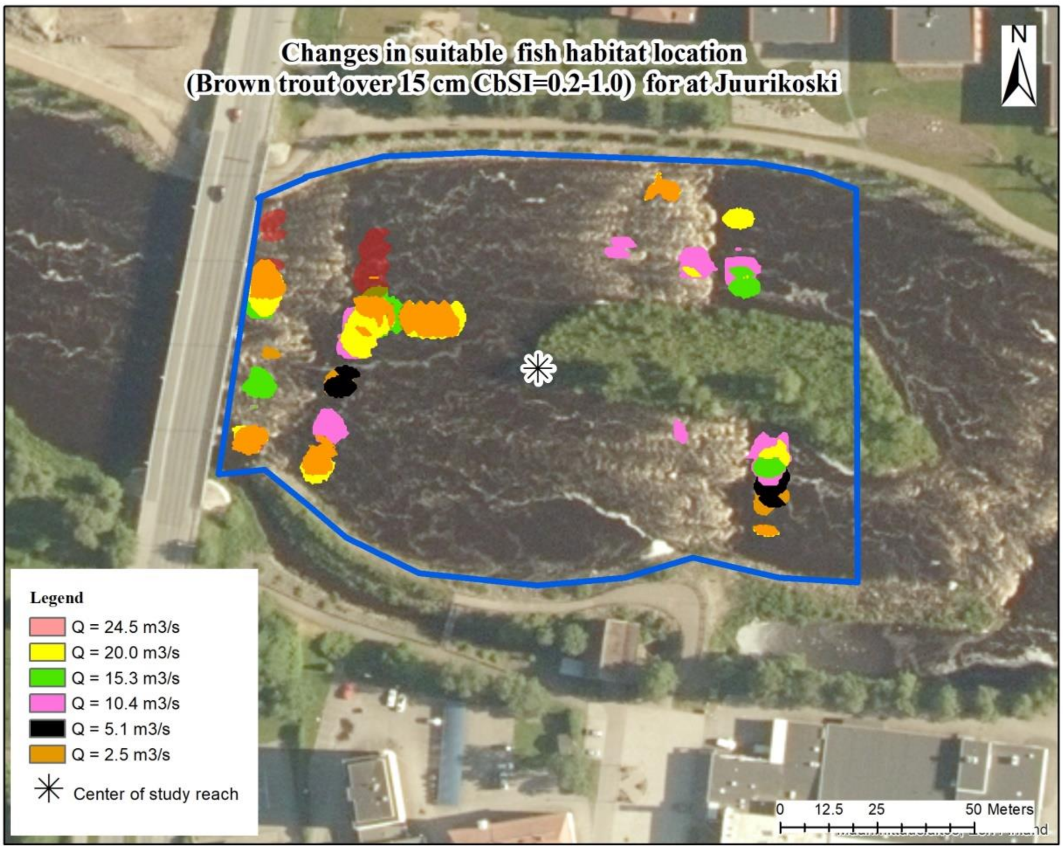
Appendix 15 Change in suitable habitat (CbSI=0.2 to 1) location at Juurikoski for brown trout under 10 cm



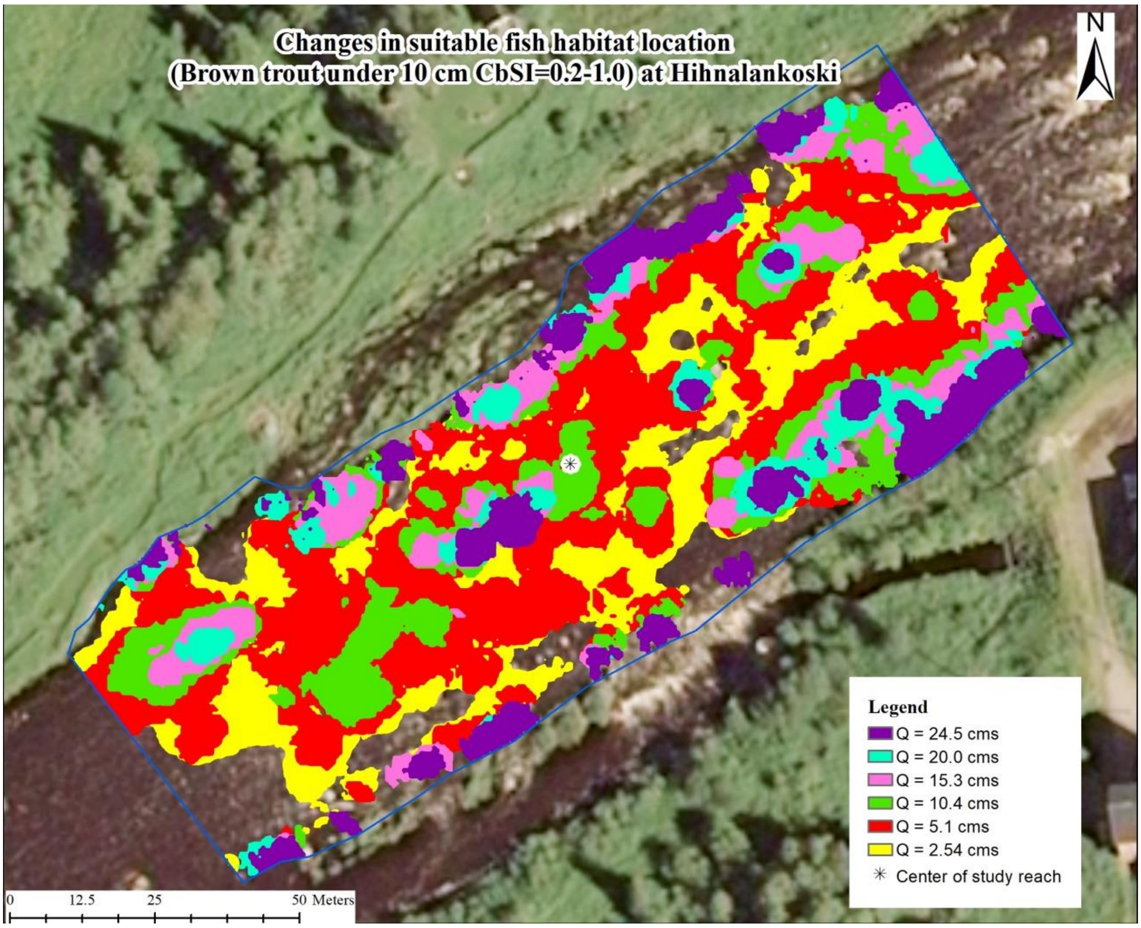
Appendix 16 Change in suitable habitat (CbSI= 0.2 to 1) location at Juurikoski for brown trout under 10 to 15 cm



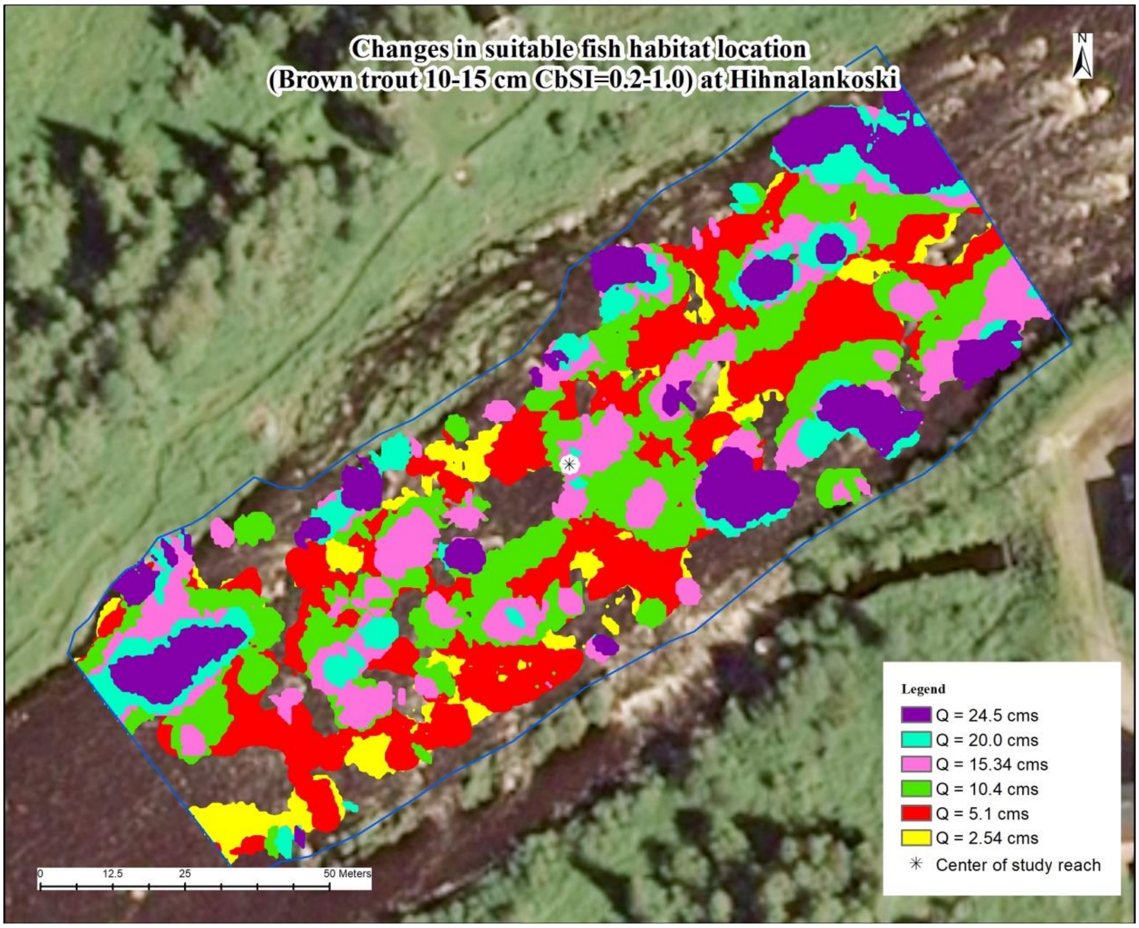
Appendix 17 Change in suitable habitat (CbSI= 0.2 to 1) location at Juurikoski for brown trout over 15 cm



Appendix 18 Change in suitable habitat (CbSI= 0.2 to 1) location at Hihnalankoski for brown trout under 10 cm



Appendix 19 Change in suitable habitat (CbSI= 0.2 to 1) location at Hihnalankoski for brown trout under 10 to 15 cm



Appendix 20 Change in suitable habitat (CbSI= 0.2 to 1) location at Hihnalankoski for brown trout over 15 cm